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Pathways for biochar carbon removal: A national foresight study

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ABSTRACT

Biochar carbon removal (BCR), achieved by stabilizing biogenic carbon through biomass pyrolysis, is gaining attention as a potential climate mitigation strategy. Yet, its future remains uncertain due to evolving market and regulatory conditions, and existing research provides limited insight into how these uncertainties interact to shape alternative deployment pathways. Using Denmark as a national case, this study combines expert interviews, stakeholder ranking, and scenario modeling to map critical uncertainties and explore plausible future pathways. Seven uncertainty categories are identified, with four emerging as critical: subsidies, carbon prices, regulations concerning biochar's agricultural use, and biomass availability. Stakeholders highlighted carbon prices and agricultural regulations as particularly decisive, which were then used for scenario development. Our results suggest that pyrolysis is relevant across all futures, but its role and scale differ markedly. Depending on the interaction between carbon prices and regulatory action, BCR may i) evolve as a large-scale carbon removal pathway, ii) shift towards non-agricultural biochar uses, iii) be confined to niche environmental applications such as sewage sludge treatment, or iv) become viable only within narrow subsidy-defined limits. These findings challenge implicit assumptions that technological readiness and rising carbon prices alone will lead to widespread BCR deployment. We demonstrate how deployment hinges on stable economic incentives and clear, predictable regulations. We conclude with recommendations for enabling the climate and environmental benefits of BCR across different plausible futures.

1. Introduction

The pathways of the Intergovernmental Panel on Climate Change (IPCC) that limit global warming to 2 °C require both the reduction of greenhouse gas (GHG) emissions and the removal of already emitted GHGs from the atmosphere [1]. An example of a carbon dioxide removal (CDR) technology that can achieve this is biochar, the solid product of biomass pyrolysis. Pyrolysis is the thermochemical conversion, at elevated temperatures and without oxygen, of organic material into biochar, bio-oil, and syngas [2–4]. It stabilizes the carbon in the biomass, enhancing its capacity for storage, for example, when applied to agricultural soils. This CDR technology is known as biochar carbon removal (BCR) [5]. Even though biochar has many different environmental applications, each with differing levels and effectiveness of carbon removal, BCR is commonly achieved by storing biochar in agricultural soils, where it can have additional agronomic and environmental benefits [5], such as reduced nutrient leaching [6] and water use efficiency [7]. The use of biochar to improve agricultural soil is its oldest known application, dating back 2000 years to the *Terra Preta de Indio*, which are man-made, black soils in the Amazon Basin showing increased fertility [8].

In Denmark, the combination of climate mitigation and agriculture is central to current biochar developments [9]. With its 2020 climate law [10], Denmark aims for a 70% reduction of its GHG emissions by 2030 compared to 1990 and net climate neutrality by 2050. Implementing this national ambition through sector-specific plans, biochar was a crucial part of the 2021 agricultural sector plan. The plan envisioned annual removal of 2 Mt (megatons or 1,000,000 tons) CO_2e (carbon dioxide equivalents) in 2030, amounting to 25% of the required sectoral emission reductions (i.e., 6–8 Mt CO_2e) and 10% of the total national reduction [9,11]. A 2024 revision lowered ambitions to 0.3–0.6 Mt CO_2e in 2030 with a subsequent increase to at least 1.2 Mt CO_2e in 2045. Even so, biochar's role as a climate mitigation strategy in Denmark remains ambitious, which has been supported through the announcement of a substantial subsidy for BCR, amounting to 10 billion DKK (1.3 billion EUR) from 2030 to 2045 [12].

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Despite these ambitions, large-scale BCR deployment in Denmark has yet to take hold and its future remains shrouded in uncertainty. This is exhibited by farmers currently only experimenting with biochar in pilot projects [9] and the first large-scale plant (exceeding 20 kt CO_2e of annual BCR) being commissioned in late 2024 [13]. These developments relate to a broader context of policy and market uncertainty since the 2021 political agreement, such as i) climate effects and marketability, ii) scale and cost of relevant biomass, iii) amount and timing of investment capital, iv) product market size and robustness, v) content and timing of Danish regulation for biochar production and use [14].

This study explores the uncertainties impacting BCR deployment in Denmark and outlines relevant pathways for future deployment through a mixed-methods approach combining expert interviews, factor ranking, workshops, and scenario modeling. While previous studies have identified barriers affecting national biochar industries [15,16], this is the first time multiple deployment scenarios have been developed. Based on the example of Denmark, we propose a methodological framework that could inform similar analyses in other geographies, contributing to global BCR deployment.

2. Method

To better understand the factors influencing the future of biochar carbon removal (BCR) in Denmark, a foresight study was undertaken. Fuerth and colleagues [17] defined foresight as "*a distinct process of monitoring prospective oncoming events, analyzing potential implications, simulating alternative courses of action, asking unasked questions, and issuing timely warning to avert risk or seize an opportunity*." It aims to produce novel and actionable insights, through the collection, aggregation, and transformation of disparate information and assumptions about the future and the validation and simulation of novel strategic options in the present. Foresight relies on interdisciplinary group discussion and participatory deliberation to establish intersubjective validation. It is commonly understood both as a toolbox of frameworks and methods, and as a capability mediated by cognitive engagement. As a toolbox, foresight includes tools such as multiple scenario development, stakeholder simulation, technology roadmapping, and innovation forecasting. As a capability mediated by cognitive engagement, each of these frames the future in the present differently, giving it concrete form through outputs such as point forecasts, scenario narratives, development plans, or plausible stakeholder actions under varying conditions. By identifying and exploring previously unthought futures, these constructions support new inquiry, conjecture development, and anticipatory action pathways. These are used to shape the future to the benefit of the organization or group, with a focus on a shared problem [18,19]. In this article, the research follows the foresight process articulated by Voros [20], continuously generating and capturing insights about the future of BCR. These are formulated and curated to serve as outputs in the form of recommendations. Fig. 1 shows the different steps undertaken, which are explained in the remainder of this section.

2.1. Sampling strategy

The sampling of experts was purposive and non-probabilistic. Purposive sampling, wherein participants are selected because they are especially knowledgeable or experienced with the topic, is used in qualitative studies that seek depth of understanding rather than statistical generalization [21,22]. Selection was guided by a sampling matrix (Table 1), developed using two common approaches to categorizing stakeholders: the quadruple helix [23] and a value chain mapping [24]. The former consists of categorizing actors into academia, industry, government, and civil society, whereas the latter categorizes them into biomass sourcing, biochar production, biochar application, carbon credits, and policy. We aimed to achieve broad and balanced coverage of the matrix rather than being completely exhaustive. Table 1 shows the expert sampling for each step of the methodology. The representation of civil society was very low due to limited interest among this stakeholder group at the present state of development.

2.2. Scanning: identifying uncertainties

The foresight process [20] takes its point of departure in a situational

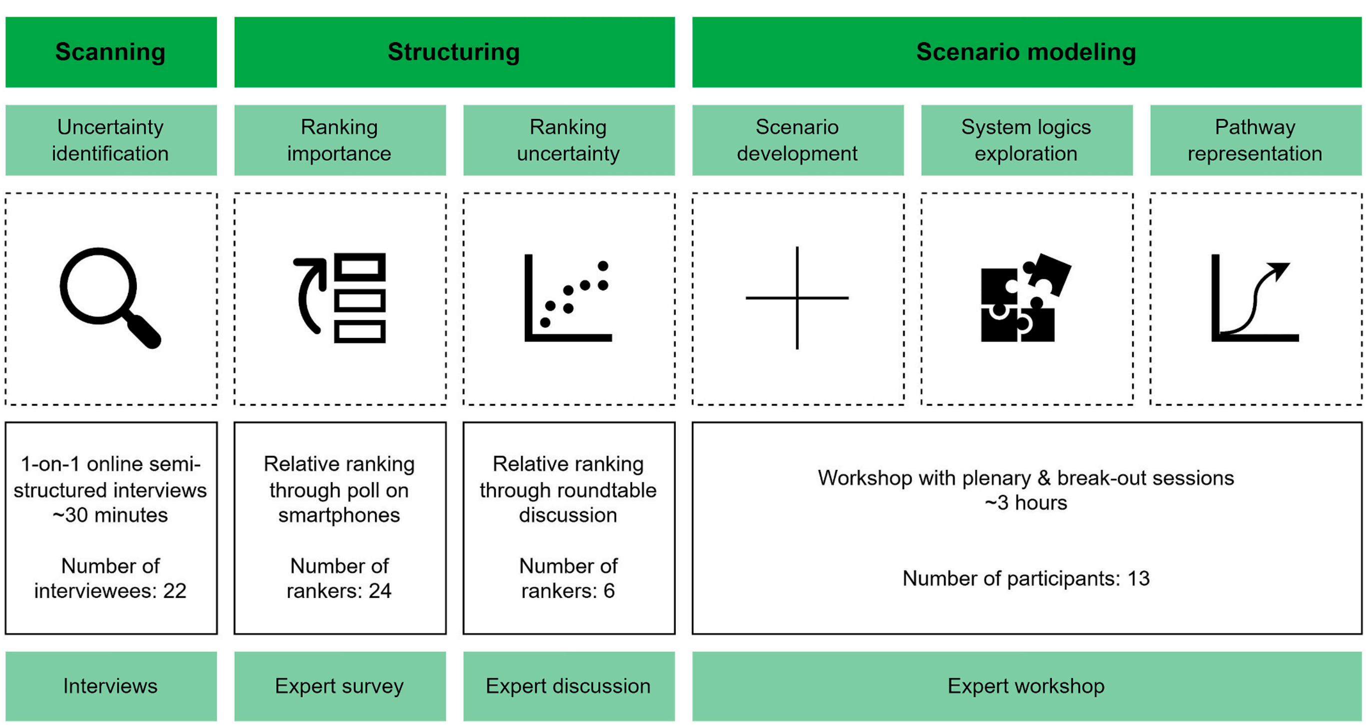

Fig. 1. Overview of the methodology.

Table 1
Overview of the expert sampling used throughout the study.

		Biomass sourcing	Biochar production	Biochar use	Carbon credits	Policy	*Total*
Scanning	**Academia**	2	1	1		1	*5*
	Industry	1	2	5	2	1	*11*
	Government		1		3	1	*5*
	Civil society					1	*1*
	Total	*3*	*4*	*6*	*5*	*4*	*22*
Ranking importance	**Academia**	1	2	4		2	*9*
	Industry		7	1		2	*10*
	Government		2	1	1	1	*5*
	Civil society						
	Total	*1*	*11*	*6*	*1*	*5*	*24*
Ranking uncertainty	**Academia**	1		1		1	*3*
	Industry			2			*2*
	Government				1		*1*
	Civil society						
	Total	*1*		*3*	*1*	*1*	*6*
Scenario modeling	**Academia**					1	*1*
	Industry	1	2	1		2	*6*
	Government		1	1	3		*5*
	Civil society		1				*1*
	Total	*1*	*4*	*2*	*3*	*3*	*13*

analysis distinguishing the known and the unknown. For identifying these boundaries, we followed van der Heijden [25], using semi-structured interviews with experts inquiring into the driving forces and uncertainties affecting BCR deployment in Denmark. These 30-minute online interviews consisted of two main parts. First, the experts were asked about their background, experience with BCR, and view on the status of BCR in Denmark, allowing for a better understanding of their answers in the second part. In this second part, the experts were asked to formulate three questions they would ask a hypothetical clairvoyant about the future of BCR in Denmark. These questions are used to elicit key uncertainties and drivers of change [26,27]. Based on the sampling strategy presented in Section 2.1, 32 experts were invited to participate in these interviews. Of them, 22 (69%) accepted, providing a total of 78 uncertainties. These were coded thematically, using an inductive coding approach, to find the main uncertainties, which are reported on in Section 3.1. There are more than three uncertainties per respondent because more respondents flagged additional uncertainties during the conversation than reported fewer than three.

2.3. Structuring: ranking uncertainties

We defined scenarios as a set of comparably different and plausible narratives about the future [28], constructed in the Intuitive Logics (IL) tradition [29,30]. This tradition was chosen because the development of exorbitant-yet-plausible scenarios challenges assumptions and stretches mental models to reframe problems for ideating novel insights, options and pathways [31]. Scenarios in this tradition are developed by identifying the most critical uncertainties to frame the scenarios [32]. This criticality was defined based on i) their importance for BCR deployment in Denmark and ii) their perceived level of uncertainty [33]. To rank the uncertainties identified in the previous step, we engaged an expert audience in two rounds at the *SkyClean Scale-up* conference in Fredericia, Denmark, as described below. The expert sampling here was not controlled and, hence, did not follow the sampling strategy presented in Section 2.1, with their participation being voluntary and based on self-selection.

2.3.1. Ranking according to importance

In the first round, all attendees in the plenary introduction session were asked to access an online poll. First, the purpose and context of the poll were described. Then, participants were asked to priority-rank the uncertainties from most to least important, using a simple Borda count. In total, 24 (100%) attendees participated in the ranking, which was carried out using Microsoft Forms embedded in PowerPoint. After completion, the attendees were shown the results of the ranking exercise and no one objected to the collective ranking. They were made aware of the possibility of discussing these uncertainties in more detail later.

2.3.2. Ranking according to uncertainty

During the second round, participants self-selected into table discussions, one of which addressed the uncertainties previously ranked by importance. To initiate the discussion, those results were drawn up on a primary axis on the table [34]. The discussion's purpose was to reposition the uncertainties along a secondary axis to assess their relative level of uncertainty. Six (25%) participants took part in this discussion, excluding two authors who served as moderators. Section 3.2 shows the results of both ranking exercises.

2.4. Scenario modeling

To uncover and articulate the dynamics and scale of BCR deployment in Denmark across a range of conditions, we developed plausible scenarios for the future and discussed how BCR might develop across them. To this end, a workshop was organized at Roskilde University, using both plenary and break-out sessions. Out of the 90 invited experts, based on the sampling strategy presented in Section 2.1, 13 (14%) participated, excluding the authors.

2.4.1. Scenario development

Having identified the critical uncertainties (Section 2.3), we returned to the IL tradition of scenario development, which calls for the assignment of diametric values to create variational analysis [35]. To accomplish this, we prototyped a series of 2 × 2 scenario matrices and worked through the strategic conversations that they afforded [25,36]. In the workshop, we brought three of these to the stakeholders for them to select one to elaborate on through exploratory dialogue [37]. Fig. 3 in Section 3.3 shows the chosen scenario matrix. In their break-out rooms, the participants were asked to develop content, including metaphors or titles for each of the four scenarios, followed by a plenary discussion.

2.4.2. System logics exploration

After this discussion, each group was assigned a single scenario to work on. Guiding questions were provided to prompt discussions about what happened to political, economic, social, and technological factors in their scenario, leading to an exploration of the core logics, narrative structures, and consequences, which were discussed and refined inter-subjectively. The groups then brought what they had discussed back to plenum, presenting their scenario, one by one, for 10 minutes, followed by a question-and-answer session lasting an additional 10 minutes. Used in this way, the scenarios are rendered as a central artifact for an inquiry system [38]. They support the probes about a range of underpinning logics that intend to identify novel framings of the nature of the problem and renew an orientation towards that problem [32]. This was continued and accomplished by the research team in post-processing, refining the logics initially sketched in the workshop into internally consistent diagrams that explain the trajectory of each scenario. The system logics for each scenario are reported on in Section 3.3 (Figs. 4-7).

2.4.3. Pathway representation

Finally, participants were introduced to the use of S-curves as a common way of representing technology deployment over time. These curves start slowly, accelerate through an inflection point, and gradually decelerate as they approach a plateau [39]. Participants were placed back into their groups and asked to sketch a possible BCR deployment pathway towards 2050 for their scenario, based on the conditions they had developed. The exercise focused on eliciting qualitative insights into how deployment could unfold, including its potential scale by 2050 and the year of strongest acceleration.

3. Results

Results are presented in three parts: i) the results from the interviews, identifying the uncertainty categories regarding the future deployment of biochar carbon removal (BCR) in Denmark, ii) the results of the ranking exercise to identify the critical uncertainties, and iii) the scenario narratives and underpinning system diagrams.

3.1. Scanning: identified uncertainties for BCR deployment in Denmark

From open coding of the interviews, which yielded 78 distinguishable uncertainties, seven overarching categories were identified. Presented below in no particular order, these are: i) subsidies for BCR, ii) carbon price, iii) regulations for agricultural use, iv) non-agricultural biochar demand, v) farmer acceptance, vi) broader public support, and vii) biomass resource availability. Although important for the economic viability of pyrolysis, energy coproducts do not constitute a separate uncertainty category but are instead considered within the carbon price uncertainty. Their importance was raised by some interviewees, but less frequently than the seven overarching categories identified above.

3.1.1. Subsidies for biochar carbon removal

This uncertainty relates mostly to the 10 billion DKK (1.3 billion EUR) subsidy politically agreed upon as part of the Green Tripartite agreement [40], to help the agricultural sector reduce its net greenhouse gas (GHG) emissions via BCR. The uncertainty is not so much related to whether the subsidy will come through, as the interviewees seemed rather certain that it would. Rather, uncertainties remain about when and how the subsidy will be rolled out, as well as who will be eligible. Interviewees repeatedly highlighted the importance of subsidy timing, as investment decisions are being postponed while awaiting clarification, particularly regarding the potential ineligibility of existing pyrolysis plants. This situation has placed Danish pyrolysis technology developers under significant financial strain, making timely subsidy implementation critical for their continued viability. Hence, subsidy clarity is not only essential for deployment speed but also for maintaining a viable developer landscape. Further uncertainty includes the potential inclusion of imported biochar, which could significantly weaken the subsidy's effectiveness in supporting domestic technology development.

3.1.2. Carbon price

The carbon price is an important uncertainty because it is crucial for the business case of pyrolysis plants that lack gate fee revenue from waste management, as can be achieved with sewage sludge pyrolysis. Such plants typically have three main revenue streams, being i) the produced biochar product, ii) the potential BCR credit of long-term carbon sequestration through biochar's end-use, and iii) the energy co-products. In Denmark, biochar's focus application is in agricultural soil. Because of its irreversibility, this is a secure and acknowledged way to realize the BCR potential. If used in Danish agricultural soil, the BCR credits are typically the main source of revenue, as the value of agricultural co-benefits is likely relatively small in such regions with fertile agricultural soils [41,42]. Despite some nutrient content, biochar's product value in a Danish agricultural context is currently low.

The carbon price results from a complex interplay of different influencing factors. On the voluntary market, Soleta [43] finds that most publicly available BCR transactions from 2021 to 2024 fell within a range of 120–190 EUR per ton CO_2, with a 2024 average of 156 EUR per ton CO_2 and substantial volatility, reinforcing the underlying uncertainty in price formation. As of May 2026, the price is 130 EUR per ton CO_2 [44]. The carbon price is also influenced by the credibility of the credits, which depends on strong and transparent certification. Varying carbon permanence measurement, gaps in emission factor methodologies, and discrepant additionality assessments further increase uncertainty regarding carbon credit validity and valuation.

The EU Carbon Removal Certification Framework (CRCF) aims to build trust in and acceptance of carbon removals by setting requirements and quality criteria, and it aims to foster transparency by creating a public registry of removals. Interviewees believed it would substantially reduce regulatory uncertainty in the long term by anchoring biochar as a source of permanent carbon removal and by defining the associated permanence standards, monitoring obligations, and sustainability requirements. Finally, carbon price uncertainty is increased by the lack of adoption of BCR in compliance frameworks. Such adoption, for example in the EU ETS, would substantially promote demand for BCR.

3.1.3. Regulations for agricultural use

The agricultural sector mainly drives the push for BCR in Denmark, seeing it as a way to offset hard-to-abate emissions, under the premise that it fits with current practices [9]. However, interviewees agreed that the large-scale application of any new substance to soil should be clearly regulated, which is not yet the case for biochar in Denmark. While other countries, such as Finland and Germany, have enacted the EU fertilizer regulation, which includes biochar, as law, the Danish Environmental Protection Agency initiated its own investigation to develop clear and concise biochar regulations by 2027 [12]. Until then, the only possibility to use biochar in Danish agricultural soil is a case-by-case permit application at the municipal level, putting the responsibility on individual local authorities and adding an additional layer of uncertainty. Interviewees highlighted that the absence of clear, national guidelines forces municipalities to interpret requirements independently, resulting in delays, inconsistent decisions, and significant administrative burden, because municipalities often lack the knowledge or mandate to assess applications efficiently. The fact that municipalities can refuse applications makes the regulatory pathway unpredictable for developers, as there is no guarantee that the biochar can be sold and applied. This also influences the sale of credits, as these require irreversibility, for example, through soil amendment. Additionally, the timing of the regulation may affect the availability of the subsidy, while its content could affect, for example, the type of biomass allowed, pyrolysis temperatures, pre- and post-treatments, and analyses like in the EU Fertilizer Regulation [45] or the European Biochar Certificate [46].

3.1.4. Non-agricultural biochar demand

Biochar has many applications other than its use in agricultural soils, all with differing levels of carbon sequestration. To qualify for BCR, the biochar must be stored in a permanent or long-term way, such as when it is applied to agricultural soil [5]. This can also be achieved in alternative uses such as concrete, asphalt, or any other type of building material [47]. Such alternative uses become even more important when biochar's use in agricultural soil remains uncertain (Section 3.1.3). With a major focus on research and development of biochar's agricultural use so far, these alternative uses are still considerably uncertain, both technically and economically. The development is fast and new alternatives emerge regularly. The ad hoc incorporation of this dynamic field into regulation and robust markets increases uncertainty.

3.1.5. Farmer acceptance

Whether farmers adopt biochar depends on several factors. First, regulatory specifications regarding where, when, and how biochar may be applied on farmland are critical for farmers' acceptance. For example, uncertainty remains regarding the actual fertilizer value of biochar in Danish agricultural practice, most notably of its phosphorus content. This value is crucial for farmers given the applicable fertilizer limits. In addition, uncertainty remains regarding biochar's overall effects on soil quality and crop productivity, leading to the ultimate question of whether biochar makes economic sense for the farmer. Even if provided to farmers at no cost, there will likely be costs associated with its use, for example, in the form of increased handling or time spent on the field. The question remains whether the benefits outweigh the costs, making biochar's use worth it for farmers. To increase acceptance, continuous field trials could provide farmers with robust, local evidence on soil and crop effects. However, farmers' willingness to participate depends not only on economic considerations, but also on issues of distributional fairness. Farmers contributing to biochar production in areas with phosphorus surplus will benefit from the improved opportunities to redistribute phosphorus. However, the carbon sink effect follows the phosphorus in the biochar, leaving a poor balance between burdens and benefits. This aligns with broader concerns that farmers would engage only if the value created by biochar, whether agronomic, environmental, or financial, remains within their own communities.

3.1.6. Broader public support

A certain level of broad societal support is relevant in two main ways. One indirect effect is the wider political support, which is particularly important regarding subsidies. More directly, it relates to the level of community support or protest around potential sites for pyrolysis plants, the not-in-my-backyard or NIMBY effect. This effect encompasses local community opposition driven by fears of reduced property values, noise, traffic, or environmental harm, even while acknowledging the project's broader societal need [48]. Other clean energy technologies have also fallen victim to the NIMBY effect, including wind turbines, solar parks, and biogas plants. The latter are particularly relevant for pyrolysis, because a possible initial BCR deployment phase in Denmark could be integrating pyrolysis of the separated and dried residue fibers into biogas plants, as seen in two cases in Northern Denmark. Furthermore, the NIMBY effect could be said to scale with scale, meaning that larger installations face disproportionately more resistance, unless paired with participatory or co-ownership models. Several interviewees mentioned how the first large-scale pyrolysis plant in Denmark received considerable public criticism due to reports of odors and negative health effects. Regarding the latter, the University Hospital in Aalborg found that these were likely due to odor violations in the start-up phase combined with anxiety from living next to unfamiliar industrial facilities [49].

3.1.7. Biomass resource availability

The biomass resource, defining how much biochar technically could be produced in Denmark, is dynamic with regard to quantity, quality, and use. The total amount of available biomass depends on policy priorities regarding land use, food systems, and nature conservation. Furthermore, prioritization will be required of competing uses for this future available biomass. Again, this depends on socio-political decisions, and it will become increasingly important in a 'de-fossilized' society, where the demand for biogenic carbon would increase.

In Denmark, the biomass resources most considered for pyrolysis include biogas residue fibers (BRF), sewage sludge, and straw. The current potential of BRF is estimated at approximately 0.5 Mt (megatons, or 1,000,000 tons) dry matter, with projections indicating a future increase to between 1.17 Mt and 1.74 Mt [14,50]. Sewage sludge is a limited resource, with an annual availability of approximately 0.1 Mt dry matter [50]. Straw constitutes the largest of the three focal feedstocks, with an estimated annual potential ranging from 1.6 Mt to 3.4 Mt dry matter [50], but no commercial straw pyrolysis plants have been built in Denmark so far. Other potential feedstocks include the woody fraction of green waste, estimated at around 0.4 Mt dry matter per year [14], and grass, a near-future candidate with a large annual potential ranging from 2.4 Mt to 8.3 Mt dry matter [50–52].

3.2. Structuring: ranked uncertainties

To identify the critical uncertainties, experts were engaged to rank the uncertainties according to their importance for BCR deployment in Denmark and their perceived level of relative uncertainty, as explained in Section 2.3. The combined result of these two ranking exercises is shown in Fig. 2, on the x- and y-axes, respectively. Four uncertainties exceeded the criticality threshold, operationalized through a diagonal decision boundary, being i) subsidies, ii) carbon price, iii) regulations for agricultural use, and iv) biomass resource availability.

The group discussion that informed the ranking according to relative uncertainty provided insights into the underlying reasoning. Notably, uncertainties perceived as being shaped by broader systemic or political dynamics were deemed more uncertain than those grounded in direct stakeholder experience. For those uncertainties perceived as highly uncertain (i.e., the carbon price, biomass availability, and non-agricultural biochar demand), this perception was attributed to complex market, policy, and societal developments. This was especially true for the carbon price and biomass availability. In the case of non-agricultural demand, uncertainty instead came from the wide range of possible development pathways linked to the breadth of potential applications. Uncertainties perceived as moderately uncertain (i.e., subsidies and regulations regarding biochar's agricultural use) were likewise felt to be beyond control of the participants but were seen as more bound by policy. Uncertainties associated with public support and farmer acceptance were considered least uncertain, reflecting a sense of familiarity and predictability through direct experience with these actors. However, the perceived farmer acceptance appears contradictory to the precautionary stance adopted by regulatory authorities and environmental organizations, calling for further evidence on long-term effects of biochar application. This discrepancy may reflect differing risk perceptions or a degree of bias in the stakeholder experiences in the discussion. Similarly, while the presence of public opposition to current projects was acknowledged, it was viewed as manageable over time, with parallels drawn to the development of the biogas sector. Therefore, these interpretations should be understood as indicative rather than definitive, reflecting perceived rather than objectively measured uncertainty. Nevertheless, they provide important context for the ranking of the uncertainties.

3.3. Scenario modeling for the future of BCR in Denmark

Three alternative scenario matrices were proposed, combining

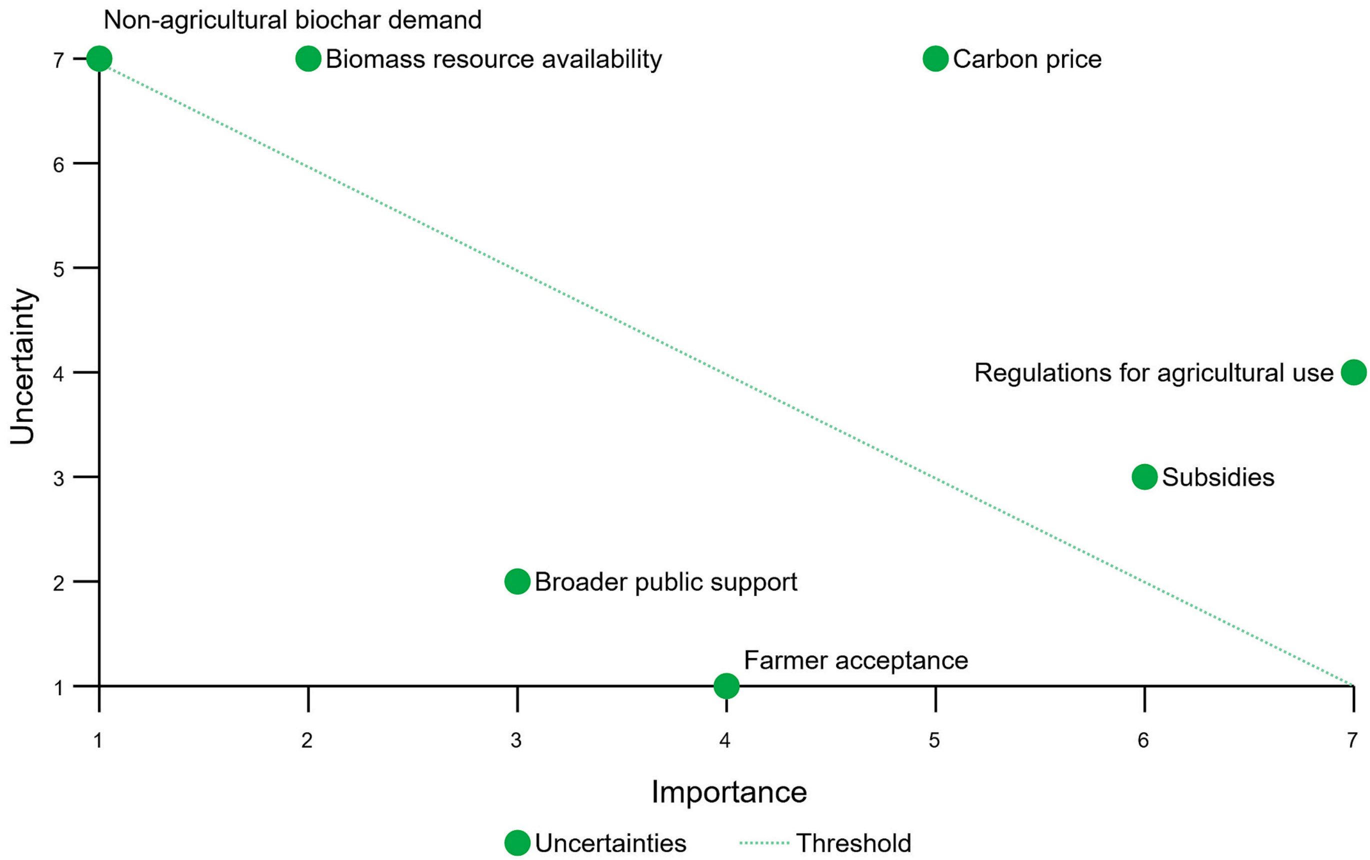

Fig. 2. Results of the ranking of the uncertainties, according to both their importance for the future deployment of biochar carbon removal in Denmark and their relative level of uncertainty.

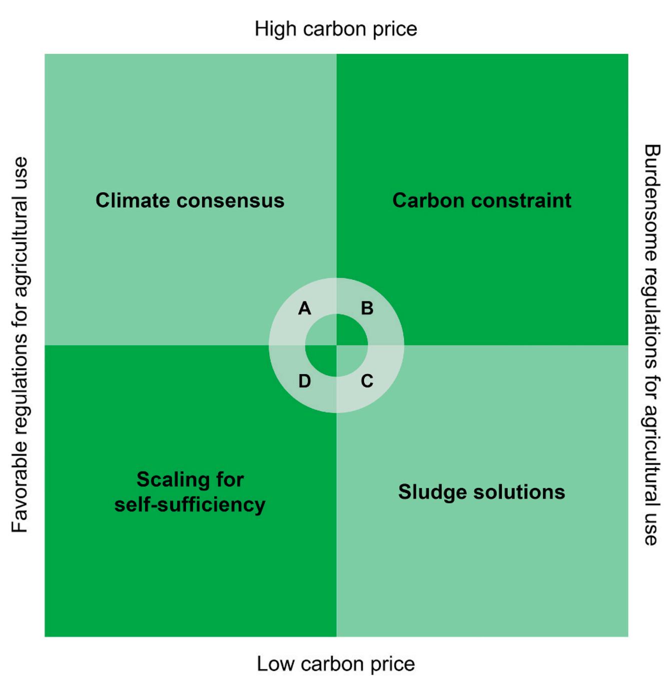

Fig. 3. Scenario matrix showing the four modeled scenarios defined by carbon price level, high versus low, and regulatory conditions for the use of biochar in agricultural soils, favorable versus burdensome.

carbon price, regulations for biochar's agricultural use, and biomass availability in pairwise configurations. The uncertainty about subsidies was omitted as it provided conversational overlap with the carbon price as an economic incentive. The participants selected the matrix defined by the carbon price and the regulations, shown in Fig. 3, as being the one that framed the most relevant conversation. The choice of axes shapes the discussion and, thereby, also affects the resulting dynamics that were explored.

3.3.1. *Scenario A: Climate consensus*

This scenario (high carbon price & favorable regulations, Fig. 4) emerges with a return to sustained geopolitical and economic stability which leads to a renewed focus on a strong green political agenda, including favorable regulations for biochar's agricultural use. These regulations rest on substantial research on the environmental effects of large-scale biochar application in agricultural soils and on societal acceptance of, and understanding of the need for, environmental technologies. The strong green political agenda, combined with international cooperation, results in the establishment of a high global carbon price of 300 EUR per ton CO_2, which is maintained through state-supported carbon credit certification schemes. The combination of high carbon prices and clear regulations reduces perceived investment risks and strengthens BCR business cases, thereby incentivizing investments, including research and development and production capacity. Market expansion is further accelerated by ongoing R&D efforts, a reduction in perceived risks through learning, and the integration of carbon capture and storage (CCS) on pyrolysis facilities. The latter development is, itself, driven by the high carbon price and continued

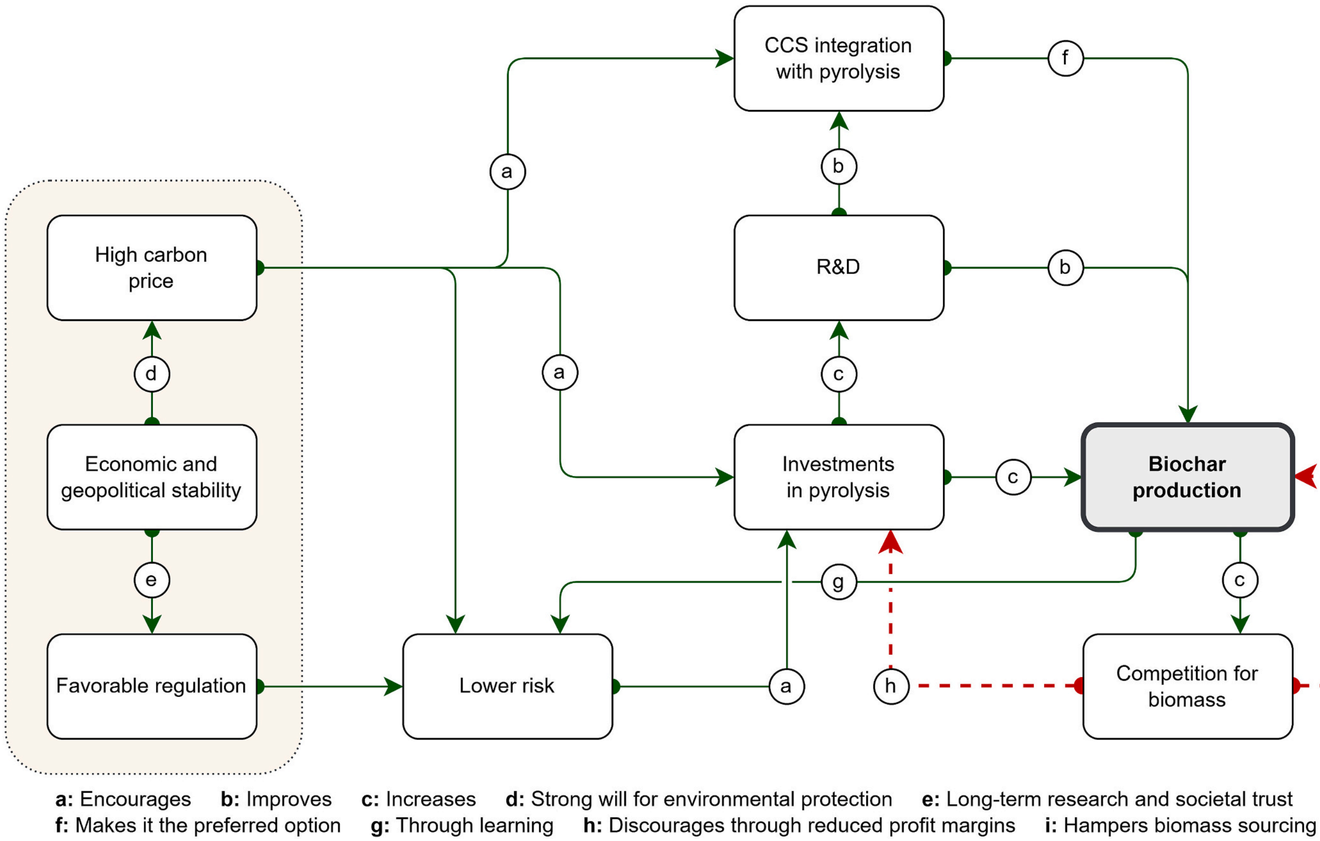

Fig. 4. System dynamics diagram for Scenario A, Climate consensus. Green arrows indicate reinforcing or enabling relationships, while red dashed arrows indicate constraining relationships. Letters provide additional information about each link, as defined in the legend below the figure. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

research. Over time, intensifying competition for biomass resources generates negative feedback effects in two main ways. First, there are fewer opportunities to sustainably source biomass for biochar production. Second, rising biomass prices lower profit margins for pyrolysis projects and make new investments less attractive. This scenario enables the largest BCR deployment, with growth unfolding progressively towards 2050, as high carbon prices, regulatory clarity, and agricultural application enhance investment and market expansion.

3.3.2. *Scenario B: Carbon constraint*

In this scenario (high carbon price & unfavorable regulations, Fig. 5), a delayed climate transition creates a policy environment characterized by urgency and prioritization of carbon dioxide removal (CDR), resulting in a high global carbon price exceeding 300 EUR per ton CO_2. Simultaneously, regulatory attention is directed towards well-understood mitigation pathways, while areas marked by uncertainty, such as the long-term effects of biochar in agricultural soils, are dealt with in a precautionary and restrictive way. Consequently, the incentives for CDR, including BCR, created by the high carbon price do not lead to adoption in Danish agriculture. Instead, alternative pathways emerge. First, biomass is primarily diverted to BECCS, where CDR per ton of biomass is higher [53,54]. Second, biochar production aims for non-agricultural applications, such as its use in concrete. Although these applications sustain demand for biochar production, the diversion of biomass to BECCS reduces feedstock availability for pyrolysis. In addition, higher-quality biomass suitable for combustion is allocated to BECCS, leaving more challenging feedstocks for pyrolysis, including BRF and sewage sludge. Because biochar produced from these feedstocks is poorly suited for some non-agricultural applications [55,56], research and development is required to adapt these biochars to these alternative uses. However, the global nature of the high carbon price encourages the export of Danish biochar and pyrolysis technology to countries where regulations governing agricultural biochar use are less restrictive, such as Germany. As growth depends on the maturation of non-agricultural biochar applications, this scenario could see a delayed but significant deployment. Once these applications become viable, deployment accelerates but remains constrained by competition with BECCS and the reduced suitability of some available feedstocks.

3.3.3. *Scenario C: Sludge solutions*

This scenario (low carbon price & unfavorable regulations, Fig. 6) emerges from a collective environmental burnout, reflecting a gradual loss of concern and motivation as individuals and institutions become overwhelmed by the persistent pressure and complexity of environmental issues. Consequently, demand for climate change mitigation decreases, and climate externalities remain weakly internalized at the global level. Denmark, still eager to boast about its position as a frontrunner in the green transition, fixes a national carbon price of 40 EUR per ton CO_2. This price level creates a risky business environment for BCR, constraining research, investments, and industrial development. The environmental burnout also means the natural environment continues to degrade. As environmental tipping points are triggered, politicians are put under local pressure to regulate sporadically. Challenges related to biochar application are addressed incrementally, as regulatory

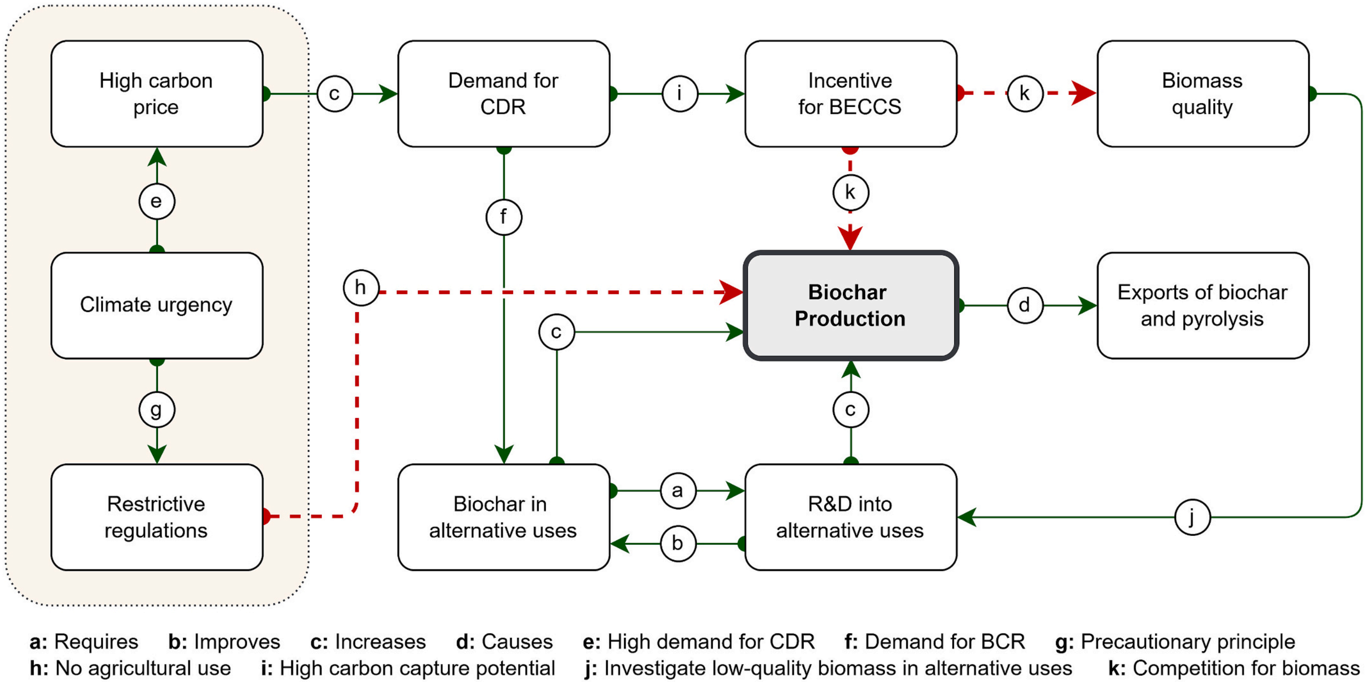

Fig. 5. System dynamics diagram for Scenario B, Carbon constraint. Green arrows indicate reinforcing or enabling relationships, while red dashed arrows indicate constraining relationships. Letters provide additional information about each link, as defined in the legend below the figure. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

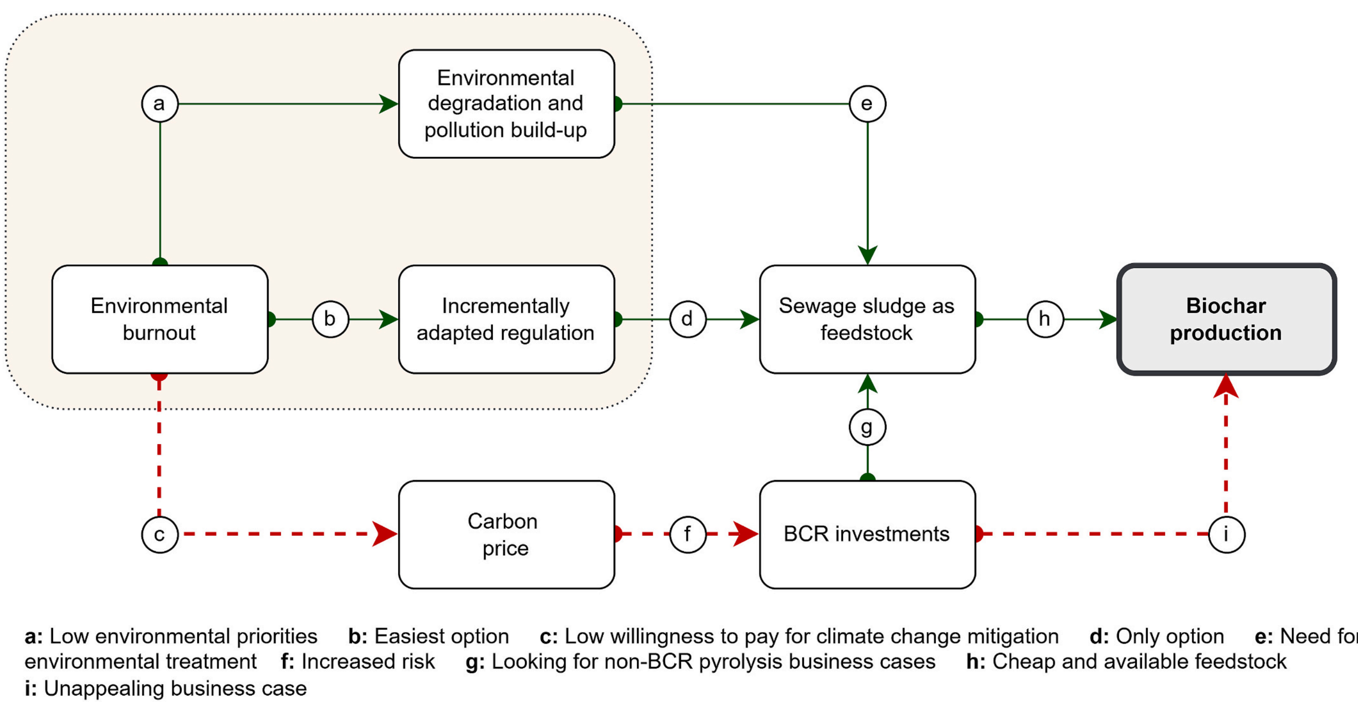

Fig. 6. System dynamics diagram for Scenario C, Sludge solutions. Green arrows indicate reinforcing or enabling relationships, while red dashed arrows indicate constraining relationships. Letters provide additional information about each link, as defined in the legend below the figure. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

agencies await long-term field trial results. Only biochar derived from sewage sludge is permitted, reflecting the capacity of pyrolysis to remove contaminants such as PFAS, thereby improving upon current practices of applying untreated sludge to agricultural land [57]. As a result, such pyrolysis plants emerge as environmental solutions, producing biochar from this highly limited resource. To enable the agricultural application of this biochar, land-use fees known from the current sludge systems are maintained to provide incentives to farmers. Because the business case for sewage sludge pyrolysis is already viable, the BCR deployment based on it emerges rapidly, while remaining niche because of the limited feedstock base.

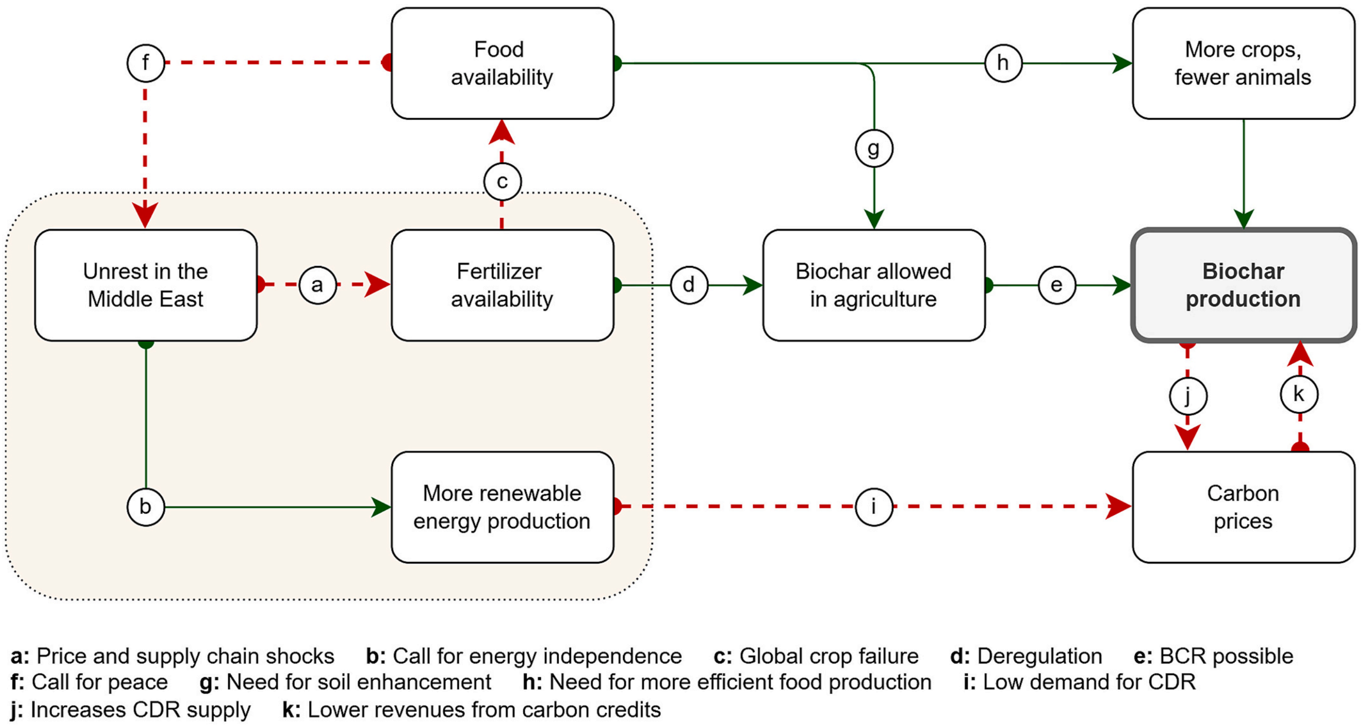

Fig. 7. System dynamics diagram for Scenario D, Scaling for self-sufficiency. Green arrows indicate reinforcing or enabling relationships, while red dashed arrows indicate constraining relationships. Letters provide additional information about each link, as defined in the legend below the figure. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

3.3.4. Scenario D: Scaling for self-sufficiency

In this scenario (low carbon price & favorable regulations, Fig. 7), extended unrest in the Middle East leads to sustained increases in global energy prices. In Denmark, as in the rest of Europe, this triggers an extreme push for energy independence, shifting focus from fossil fuels towards renewable energy. Incidentally, the transition towards a carbon-neutral economy accelerates, reducing overall CDR demand. This reduced demand lowers carbon prices, diminishing revenues for pyrolysis plants. Simultaneously, the expansion of renewable energy capacity incentivizes utilization of biomass for energy rather than biochar production. However, biochar production is sustained through another driver. Global fertilizer shortages follow from stagnating production in the Middle East. As agricultural yields decline due to limited access to affordable fertilizers, a global food shortage emerges, increasing the need for alternative soil enhancement options. This fertilizer shortage, together with a broader crisis-driven deregulation, leads to fast-tracked acceptance of biochar's agricultural use. Biochar thus becomes both permitted and required as a soil amendment, increasing demand. In addition, the global food shortage drives a transition from animal-based to plant-based calorie production, increasing the availability of biomass residues for applications such as pyrolysis. Despite the presence of drivers for pyrolysis deployment, the economic viability of BCR remains largely dependent on the subsidy that already has been promised today. Therefore, this scenario could see a very low deployment, bound by the pace and limits of the subsidy.

4. Discussion

Our findings revealed a wide range of uncertainties regarding the deployment of biochar carbon removal (BCR) in Denmark, but pyrolysis technology itself was not perceived as a major one. Interviewees expressed confidence in its maturity and emphasized the strategic importance of Danish technologies for handling widely available feedstocks of specific domestic relevance, such as biogas residue fibers (BRF) and sewage sludge. This aligns with a global review emphasizing that BCR deployment depends on feedstock-specific value chains [58]. It also corresponds with earlier work on BCR in Denmark [14], suggesting that several uncertainties identified previously remain unresolved. Rather than technological feasibility, the persistent uncertainties are primarily economic and regulatory in nature. These are closely interlinked, as a lack of regulatory clarity increases the perceived investment risk. Therefore, the central question is no longer about technical feasibility, but whether regulatory clarity, market incentives, and societal acceptance can align to support a viable and stable business case.

A critical barrier remains the regulatory approval of biochar's agricultural application in Denmark. Regardless of their validity, uncertainties about unexpected long-term environmental impacts of large-scale biochar use constrain deployment. However, the need for long-term, context-specific field data introduces a temporal tension with climate objectives. Waiting until sufficient evidence is available may reduce uncertainty, but it also delays climate mitigation, potentially affecting national targets and global effects. A similar tension exists concerning the BCR subsidy, whose timing and design are crucial. Delays may hinder industry development, while design choices may affect the domestic technology developer landscape. This is particularly relevant given the strategic importance of Danish technologies for local feedstocks. A sufficiently high and stable carbon price remains a key driver for BCR, as carbon credits are an important revenue stream, covering between 20% and 50% of production costs [59]. In addition to these economic and regulatory dimensions, uncertainty also persists regarding biomass availability. While having a biophysical basis, it is shaped by broader socio-political decisions concerning land use, agricultural systems, and competing uses. This finding is supported by Ronix and colleagues [15] and Pierson and colleagues [16]. Both use qualitative approaches similar to ours, including interviews and workshops, but for the United States and Brazil, respectively. A methodological difference is that both studies derive their recommendations directly from the barriers, whereas ours come from the scenarios based on these uncertainties. They identify barriers such as inconsistent or uncertain regulations, permitting difficulties, lack of economic incentives, logistical bottlenecks, insufficient field trials, and limited public understanding and acceptance. These similarities suggest that the uncertainties identified in our Danish case are not unique but recur across different contexts. Unlike our findings, both studies also identify technology as a barrier, although this should be interpreted carefully. In the American case [16], technology is the least emphasized barrier, while in the Brazilian case [15], the uncertainty relates primarily to access to production technology. There, application technology is also uncertain but largely because Brazil lacks national methodologies for field application, linking the issue more to regulation. These studies also strengthen the conclusion from our scenarios that pyrolysis can develop in different directions, from carbon removal in agriculture in Denmark and Brazil to forest waste and wildfire management in the United States.

A recent review of biochar commercialization identifies similar levers for scaling BCR globally, including regulatory consistency, subsidies, carbon credits, and suitable feedstock [58]. However, they consider them separately rather than examining their interaction. The importance of such interaction is illustrated by Pourhashem and colleagues [60], showing that policies in the United States influenced not only the rate and scale of technological deployment, but also its direction. This supports the central insight from our scenarios that markedly different biochar industries could emerge. This variability is already visible in the Nordic biochar sector, where Salo and colleagues [59] distinguish six business models, including carbon removal and waste-to-resource. From the same Nordic perspective, they identify uncertainties similar to ours, including regulations, carbon pricing, feedstock availability, and user awareness. However, they also identify plant reliability as a technological concern. Although not based on a dedicated scenario workshop, their future development pathways align closely with our scenarios: one is based on carbon removal, one on circular economy and waste valorization, and one on market dynamics. The latter is comparable to our scenario with fertilizer shortages. Similarly, Salo and colleagues [61] identify influencing factors such as uncertain profitability, limited awareness, and policy gaps. While these studies identify similar uncertainties, they differ from our work by treating biochar primarily at the firm level, whereas we treat it on a national level.

Compared to earlier work focusing on Denmark [14], our findings highlight the growing importance of social factors, particularly farmer acceptance and broader public support. While these were deemed more important than biomass availability, they were simultaneously perceived as less uncertain, or more manageable. The importance of these factors may indicate maturation beyond technical concerns. This is supported by the commissioning of the first large-scale pyrolysis plant in Denmark in late 2024, demonstrating technological readiness and making the industry more visible to society. The ranking exercise also underlines the complexity of the BCR system, which remains highly dependent on external and evolving conditions. This is illustrated by apparent discrepancies between stakeholder groups. For example, farmers, who are relatively close to industry, were generally perceived as willing to adopt biochar, whereas regulatory authorities and environmental organizations, positioned more externally, were deemed more cautious. This highlights the extent to which the development is shaped also by external perceptions, institutional processes, and public legitimacy.

Qualitative approaches to uncertainty, such as the one used here, are just one way to study future deployment. Wiest and colleagues [62], for example, model biomass use in the Swiss energy system across 1000 future scenarios, with biochar as one option. Like us, they reject a single deterministic future and investigate robustness across multiple scenarios. However, they assess uncertainty through quantitative optimization, whereas we use participatory scenario development to capture regulatory, social, market, and perception uncertainties that are difficult to represent in such models.

4.1. Recommendations

Recommendations follow from the mapped uncertainties and the developed scenarios (Table 2). Some of those enable BCR's most prolific scenario, with high carbon prices and favorable regulations for biochar's agricultural use. The latter is achieved by clear and dedicated rules for biochar's production and use, which should be supported by continuous field testing. When pyrolysis reduces toxicity, for example with sewage sludge [57] or biogas digestate [63], regulations should prioritize the use of biochar over the direct use of the polluted biomass in agricultural soil. A compliance market for carbon credits can strengthen demand, increasing carbon prices. It should align with Denmark's overall economic structure [64] and be state-regulated on the national, European (e.g., integration into the European Union's Emission Trading Scheme), or global level.

Other recommendations follow from desirable actions in each scenario and their outcomes in the other scenarios, as they may be shared across scenarios while being justified differently given each scenario's inherent logics. For example, continuous field testing can reassure stakeholders for large-scale biochar deployment (Scenario A), prove its fertilizer value (Scenario D), or demonstrate its effectiveness in treating sewage sludge (Scenario C).

Investigations are also necessary on how to create value from biomass pyrolysis beyond biochar's carbon sequestration, including

Table 2
Overview of recommendations. The first column after the recommendations identifies the first three recommendations as necessary enablers to reach the most prolific BCR pathway (Scenario A, Climate consensus). The scenario columns indicate whether each recommendation is expected to have a positive (↑), negative (↓), or neutral (→) effect in each scenario. No-regret actions avoid negative consequences across all scenarios, whereas risky bets may be beneficial in some scenarios but disadvantageous in others [68].

	Recommendation	Enabler	Scenario A	Scenario B	Scenario C	Scenario D	Classification
1	Carbon credit compliance market	×	*Na*	*Na*	*Na*	*Na*	No-regret
2	Dedicated biochar regulations	×	*Na*	*Na*	*Na*	*Na*	No-regret
3	Continuous field testing	×	↑	→	→	↑	No-regret
4	Investigate biochar's value beyond carbon sequestration		↑	↑	↑	↑	No-regret
5	Investigate biochar's fertilizer potential		↑	→	→	↑	No-regret
6	Design a transformative subsidy		→	→	↑	↑	No-regret
7	Ensure optionality for pyrolysis		→	↑	↑	↑	No-regret
8	Technology exports		→	↑	↑	↑	No-regret
9	Offtake agreements		↑	↓	↓	↓	Risky bet
10	Communication and stakeholder engagement		↑	↑	↑	↑	No-regret
11	Invest in human resources		↑	→	→	→	No-regret

advanced energy valorization, specialty chemicals, advanced and cascading biochar use, and the integration of pyrolysis in biorefineries. For example, biochar can be used in anaerobic digestion [65] or as a filter for H_2S [66] before being applied to agricultural soil. This is particularly important in scenarios with limited economic incentive from carbon credits but also helps in other scenarios, as diversified income streams are crucial for financial viability [59]. Even in the most prolific BCR scenario, biomass use efficiency should be maximized, keeping pyrolysis relevant compared to other technologies. A specific example of additional value is biochar's product value as soil improver and fertilizer, which is particularly useful in Scenario D. Research efforts could include fuel design studies to optimize biochar's fertilizer value and the development of refined fertilizers or sophisticated soil enhancers based on biochar. Improving biochar's fertilizer potential may both provide additional value and mitigate fertilizer shortages in Scenario D, while developing ways to extract phosphorus from biochar may increase biochar application rates in scenarios with large nutrient surplus (Scenario A). Because of its limited soil application in Scenarios B and C, biochar's fertilizer value is less critical there.

In Scenario D, the design of BCR subsidy schemes is important because it may provide the primary economic driver. To nurture a pyrolysis sector, the subsidy scheme should steer technology and value chain development towards sound business cases on market terms before the subsidy is phased out. Furthermore, it should be aligned with the broader regulatory landscape allowing for flexibility regarding cascading use of biochar. In general, technological and regulatory optionality should be considered, including flexibility regarding the type of biomass used, as well as flexibility between BCR and energy production with carbon capture and storage (CCS). Technology exports increase technological resilience by providing alternative market opportunities. They are particularly relevant in Scenarios B and C, with limited biochar use in Danish agricultural soils. In Scenario C, exports may be premised on the fact that polluted resources like sewage sludge constitute a global problem. Exports can be anticipated by developing patent bundles, international partnerships, or potentially relocating operations. Offtake agreements for biomass, biochar, or energy are meant to prepare for scaling in Scenario A. In other scenarios, they add risk, as businesses might not be able to fulfill them and society might end up in a technological lock-in for a scarce resource.

Finally, communication and stakeholder engagement should not be overlooked. Ties with the public, and farmers in particular, are important in all scenarios. In Scenario A, for example, the bigger scale entails a larger need for land-owning partners and bigger consequences of failure. Establishing a think-tank could improve dissemination and myth-busting, while living lab structures with frontrunning farmers and consultants can support practical learning, awareness-building, and social acceptance [67]. These recommendations align with previous ones to improve science dissemination [16] and to include farmers more closely [60]. International relations and policy harmonization are particularly relevant in Scenarios B and C. National partnerships could help scale the domestic value chain in Scenario A and support investigations of non-agricultural biochar applications in Scenario B. Finally, staffing and competencies could be a bottleneck in Scenario A, warranting human resources investments.

5. Conclusions

The future development of biochar carbon removal (BCR) in Denmark is influenced by many uncertainties, with the most critical ones being i) subsidies, ii) carbon prices, iii) regulations governing biochar's agricultural use, and iv) biomass availability. These were perceived as being shaped more by broader systemic and political dynamics than by direct stakeholder influence. The developed scenarios illustrate different plausible pathways for BCR deployment in Denmark. All pathways see a role for BCR in Denmark, but with extensive variation in scale and timing. Carbon prices mostly govern the scale, while the establishment of favorable agricultural regulations sets the direction of deployment, depending more on this interplay between economic incentives and regulatory clarity than on technological readiness. This means that predictable rules for agricultural application and a stable carbon price are essential for establishing a viable business case. To ensure that Denmark can capture BCR's climate benefits, as envisioned politically, industry, researchers and policymakers must work towards reducing investment risk and optimizing value creation in the relevant deployment context.

CRediT authorship contribution statement

L. Campion: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **M.J. Spaniol:** Writing – review & editing, Methodology, Investigation, Conceptualization. **T.P. Thomsen:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

While preparing this work, ChatGPT was used to improve writing. The authors take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] K. Calvin, D. Dasgupta, G. Krinner, A. Mukherji, P.W. Thorne, C. Trisos, et al., in: Core Writing Team, H. Lee, J. Romero (Eds.), Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change 2023, IPCC, IPCC, Geneva, Switzerland, 2023, https://doi.org/10.59327/IPCC/AR6-9789291691647.
[2] J. Rogelj, D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, et al., Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development, in: V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, et al. (Eds.), Global Warming of 1.5°C, Cambridge University Press, 2018, pp. 93–174, https://doi.org/10.1017/9781009157940.004.
[3] J. Lehmann, Bio-energy in the black, Front. Ecol. Environ. 5 (2007) 381–387, https://doi.org/10.1890/1540-9295(2007)5[381:bitb]2.0.co;2.
[4] V. Bridgwater A, Catalysis in thermal biomass conversion, Appl. Catal. A Gen. (1994), https://doi.org/10.1016/0926-860X(94)80278-5.
[5] D. Chiaramonti, J. Lehmann, F. Berruti, P. Giudicianni, H. Sanei, O. Masek, Biochar is a long-lived form of carbon removal, making evidence-based CDR projects possible, Biochar 6 (2024), https://doi.org/10.1007/s42773-024-00366-7.
[6] M. Bekchanova, L. Campion, S. Bruns, T. Kuppens, J. Lehmann, M. Jozefczak, et al., Biochar improves the nutrient cycle in sandy-textured soils and increases crop yield: a systematic review, Environ. Evid. 13 (2024), https://doi.org/10.1186/s13750-024-00326-5.
[7] Y. Gao, G. Shao, J. Lu, K. Zhang, S. Wu, Z. Wang, Effects of biochar application on crop water use efficiency depend on experimental conditions: a meta-analysis, Field Crop Res. 249 (2020), https://doi.org/10.1016/j.fcr.2020.107763.
[8] B. Glaser, J.J. Birk, State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de índio), Geochim. Cosmochim. Acta 82 (2012) 39–51, https://doi.org/10.1016/j.gca.2010.11.029.
[9] I.M. Hougaard, Enacting biochar as a climate solution in Denmark, Environ. Sci. Pol. 152 (2024), https://doi.org/10.1016/j.envsci.2023.103651.
[10] DK Government, Klimaloven [Climate Act], 2020.

[11] DK Government, Aftale om grøn omstilling af dansk landbrug [Agreement on the green transition of Danish agriculture], 2021.
[12] DK Government, Strategi og arbejdsprogram for pyrolyse [Strategy and work program for pyrolysis], 2024.
[13] T. Christensen, Pyrolyse bliver kaldt landbrugets store håb: Nu er Danmarks største anlæg indviet i Nordjylland [Pyrolysis is being called agriculture's great hope: Denmark's largest plant has now been inaugurated in North Jutland], . DR, 2024.
[14] CIP Foundation, How to establish a market for CCS with biochar in Denmark, 2024.
[15] A. Ronix, C. Michelin, E. Carvalho, C.C. Cerri, O. Faria, A. Bogado, et al., Perspectives and opportunities for the intensive use of biochar in Brazil, Environ. Res. Lett. (2026), https://doi.org/10.1088/1748-9326/ae36c4.
[16] D. Pierson, N. Anderson, J. Brewen, N. Clark, M.C. Hardy, D. McCollum, et al., Beyond the basics: a perspective on barriers and opportunities for scaling up biochar production from forest slash, Biochar 6 (2024), https://doi.org/10.1007/s42773-023-00290-2.
[17] L.S. Fuerth, E.M. Faber, Anticipatory Governance Practical Upgrades: Equipping the Executive Branch to Cope with Increasing Speed and Complexity of Major Challenges, 2012.
[18] M.J. Spaniol, Organizing foresight tools, World Futures Rev. 16 (2024) 261–276.
[19] M. Cristofaro, M. Augier, L. Leoni, Generative artificial intelligence for managerial foresight, Futures 180 (2026) 103831, https://doi.org/10.1016/j.futures.2026.103831.
[20] J. Voros, A generic foresight process framework, Foresight 5 (2003) 10–21.
[21] L.A. Palinkas, S.M. Horwitz, C.A. Green, J.P. Wisdom, N. Duan, K. Hoagwood, Purposeful Sampling for Qualitative Data Collection and Analysis in Mixed Method Implementation Research, Adm. Policy Ment. Health Ment. Health Serv. Res. 42 (2015) 533–544, https://doi.org/10.1007/s10488-013-0528-y.
[22] M. Ahmad, S. Wilkins, Purposive sampling in qualitative research: a framework for the entire journey, Qual. Quant. 59 (2025) 1461–1479, https://doi.org/10.1007/s11135-024-02022-5.
[23] A. Galvao, C. Mascarenhas, C. Marques, J. Ferreira, V. Ratten, Triple helix and its evolution: a systematic literature review, Journal of Science and Technology Policy Management 10 (2019) 812–833, https://doi.org/10.1108/JSTPM-10-2018-0103.
[24] M.M.C. Fritz, R. Rauter, R.J. Baumgartner, N. Dentchev, A supply chain perspective of stakeholder identification as a tool for responsible policy and decision-making, Environ. Sci. Pol. 81 (2018) 63–76, https://doi.org/10.1016/j.envsci.2017.12.011.
[25] K. van der Heijden, Scenarios: the art of strategic conversation, 2nd ed, John Wiley & Sons, 2005.
[26] C.N. Cook, S. Inayatullah, M.A. Burgman, W.J. Sutherland, B.A. Wintle, Strategic foresight: How planning for the unpredictable can improve environmental decision-making, Trends Ecol. Evol. 29 (2014) 531–541, https://doi.org/10.1016/j.tree.2014.07.005.
[27] Kedge, Strategic Foresight Primer, 2017.
[28] M.J. Spaniol, N.J. Rowland, Defining scenario, Futures Foresight Sci. 1 (2019) e3, https://doi.org/10.1002/ffo2.3.
[29] R. Bradfield, G. Wright, G. Burt, G. Cairns, K. van der Heijden, The origins and evolution of scenario techniques in long range business planning, Futures 37 (2005) 795–812, https://doi.org/10.1016/j.futures.2005.01.003.
[30] P. Wack, Scenarios: uncharted waters ahead, Harv. Bus. Rev. 63 (1985) 72–89.
[31] P.J.H. Schoemaker, Multiple scenario development: Its conceptual and behavioral foundation, Strateg. Manag. J. 14 (1993) 193–213, https://doi.org/10.1002/smj.4250140304.
[32] R. Ramirez, A. Wilkinson, Strategic Reframing: The Oxford Scenario Planning Approach, Oxford University Press, 2016.
[33] T. Wulf, P. Meissner, S. Stubner, A Scenario-based Approach to Strategic Planning: Integrating Planning and Process Perspective of Strategy, Leipzig, 2010.
[34] J. Derbyshire, G. Wright, Augmenting the intuitive logics scenario planning method for a more comprehensive analysis of causation, Int. J. Forecast. 33 (2017) 254–266, https://doi.org/10.1016/j.ijforecast.2016.01.004.
[35] G. Ringland, Scenario planning: managing for the future, 1st ed, Wiley, 1998.
[36] N.J. Rowland, M.J. Spaniol, The future multiple, Foresight 17 (2015) 556–573, https://doi.org/10.1108/FS-02-2015-0014.
[37] N.J. Rowland, M.J. Spaniol, Social foundation of scenario planning, Technol Forecast Soc Change 124 (2017) 6–15, https://doi.org/10.1016/j.techfore.2017.02.013.
[38] C.W. Churchman, The design of inquiring system, Basic Books, New York, 1971.
[39] X. Li, R. Chang, J. Zuo, Y. Zhang, How does residential solar PV system diffusion occur in Australia? A logistic growth curve modelling approach, Sustain. Energy Techn. and Assess. 56 (2023), https://doi.org/10.1016/j.seta.2023.103060.
[40] DK Government, Aftale om et Grønt Danmark [Agreement on a Green Denmark], 2024.
[41] J.W.M. Pullens, P. Sørensen, B. Melander, J.E. Olesen, Legacy effects of soil fertility management on cereal dry matter and nitrogen grain yield of organic arable cropping systems, Eur. J. Agron. 122 (2021), https://doi.org/10.1016/j.eja.2020.126169.
[42] N. Zhang, X. Ye, Y. Gao, G. Liu, Z. Liu, Q. Zhang, et al., Environment and agricultural practices regulate enhanced biochar-induced soil carbon pools and crop yield: a meta-analysis, Sci. Total Environ. 905 (2023), https://doi.org/10.1016/j.scitotenv.2023.167290.
[43] C. Soleta, Carbon Removal Credits: Current and Future Value Development on Voluntary and Compliance Markets with a Focus on Scaling Biochar Carbon Removals in the EU, DTU, 2025.
[44] Puro.earth, CORC Carbon Removal Indexes. https://puro.earth/buy-carbon-credits/removal-certificate-corc/carbon-removal-indexes/, 2026. (Accessed 3 July 2026).
[45] L. Štrubelj, Waste, Fertilising Product, or Something Else? EU Regulation of Biochar, Journal of Environmental Law 34 (2022) 529–540, https://doi.org/10.1093/jel/eqac013.
[46] EBC, European Biochar Certificate – Guidelines for a Sustainable Production of Biochar (Version 10.5E), Carbon Standards International (CSI), Frick, Switzerland, 2025.
[47] K.I. Ogunwa, E.C. Nnadozie, N. Dube, P.O. Oladoye, K.S. Obayomi, The evolving role of biochar: recent advances and future directions - a review, Biomass Bioenergy 208 (2026), https://doi.org/10.1016/j.biombioe.2025.108844.
[48] S. Carley, D.M. Konisky, Z. Atiq, N. Land, Energy infrastructure, NIMBYism, and public opinion: a systematic literature review of three decades of empirical survey literature, Environ. Res. Lett. 15 (2020), https://doi.org/10.1088/1748-9326/ab875d.
[49] Aalborg University Hospital, Rapport vedrørende symptomer hos borgere omkring Stiesdal SkyClean pyrolyseanlaeg og Agri Energy biogasanlaeg i Smidstrup, Aalborg, 2025.
[50] L. Elsgaard, A.P.S. Adamsen, H.B. Møller, A. Winding, U. Jørgensen, E. Ø. Mortensen, et al., Knowledge synthesis on biochar in Danish agriculture, 2022.
[51] G. Ravenni, T.P. Thomsen, A.M. Smith, M. Ambye-Jensen, K.T. Rohde-Nielsen, U. B. Henriksen, Integration of a drying and pyrolysis system in a green biorefinery: biochar product quality and impacts on the overall energy balance and climate footprint, Biomass Convers. Biorefinery 14 (2024) 25143–25159, https://doi.org/10.1007/s13399-023-04877-4.
[52] T.P. Thomsen, M.B. Karlsson, A. Kamp, Integration of green biorefineries and pyrolysis: climate footprint assessment of co-management of grass pulp and cattle manure in Denmark, Waste Biomass Valor. (2025), https://doi.org/10.1007/s12649-025-03249-5.
[53] S. Chiquier, P. Patrizio, M. Bui, N. Sunny, N. Mac Dowell, A comparative analysis of the efficiency, timing, and permanence of CO2 removal pathways, Energy Environ. Sci. 15 (2022) 4389–4403, https://doi.org/10.1039/d2ee01021f.
[54] L. Zakrisson, E.S. Azzi, C. Sundberg, Climate impact of bioenergy with or without carbon dioxide removal: influence of functional unit and parameter variability, Int. J. Life Cycle Assess. 28 (2023) 907–923, https://doi.org/10.1007/s11367-023-02144-2.
[55] G. Murali, L.S. Wong, A comprehensive review of biochar-modified concrete: mechanical performance and microstructural insights, Constr. Build. Mater. 425 (2024), https://doi.org/10.1016/j.conbuildmat.2024.135986.
[56] S.B. Kang, H. Do Yun, W. Choi, Feasibility on diverse biochars as supplementary cementitious materials, Sci. Rep. 15 (2025), https://doi.org/10.1038/s41598-025-24618-z.
[57] E.D. Thoma, R.S. Wright, I. George, M. Krause, D. Presezzi, V. Villa, et al., Pyrolysis processing of PFAS-impacted biosolids, a pilot study, J. Air Waste Manage. Assoc. 72 (2022) 309–318, https://doi.org/10.1080/10962247.2021.2009935.
[58] S.S. Senadheera, P.A. Withana, S. You, D.C.W. Tsang, S.Y. Hwang, Y.S. Ok, Sustainable biochar: market development and commercialization to achieve ESG goals, Renew. Sust. Energ. Rev. 217 (2025), https://doi.org/10.1016/j.rser.2025.115744.
[59] E. Salo, M. Ghoreishi, J. Raitila, M. Jalas, A. Markkula, A. Näyhä, Emerging business models of Nordic biochar producers: a sustainable business model typology, J. Circ. Econ. 4 (2026), https://doi.org/10.55845/joce-2026-41335.
[60] G. Pourhashem, S.Y. Hung, K.B. Medlock, C.A. Masiello, Policy support for biochar: Review and recommendations, GCB Bioenergy 11 (2019) 364–380, https://doi.org/10.1111/gcbb.12582.
[61] E. Salo, K. Weber, M. Hagner, A. Näyhä, Nordic perspectives on the emerging biochar business, J. Clean. Prod. 475 (2024), https://doi.org/10.1016/j.jclepro.2024.143660.
[62] G. Wiest, N. Nolzen, F. Baader, A. Bardow, S. Moret, Low-regret strategies for energy systems planning in a highly uncertain future, Cell Rep. Sustain. (2025), https://doi.org/10.1016/j.crsus.2025.100585.
[63] R. Rossi, G. Ravenni, P. Godlewska, C.B.M. Lade, K. Kostadinova, H. Birch, et al., Investigation of environmental issues related to the production and use of biochar - Executive summary of feedstock and biochar analysis, APA, 2026, https://doi.org/10.11581/65841874-5e4c-4b7c-9197-b162b2b79e2d.
[64] D. Driscoll, Why Carbon Taxes Failed, Oxford University Press, 2026, https://doi.org/10.1093/9780197823569.001.0001.
[65] P. Devi, C. Eskicioglu, Effects of biochar on anaerobic digestion: a review, Environ. Chem. Lett. 22 (2024) 2845–2886, https://doi.org/10.1007/s10311-024-01766-8.
[66] A.D. Martin, G. Ravenni, T.P. Thomsen, Low-cost hydrogen sulfide removal with biochar and activated biochar, Next Research 2 (2025) 100286, https://doi.org/10.1016/j.nexres.2025.100286.
[67] A.K. Aare, S.R. Hansen, Living labs in agrifood studies: an opportunity to revisit fundamental questions about participatory research? Agric. Syst. 219 (2024) https://doi.org/10.1016/j.agsy.2024.104058.
[68] M.J. Spaniol, Using scenarios to assess innovations, in: Technology foresight for public funding of innovation: Methods and best practices, European Commission. Joint Research Centre, 2023, pp. 59–65, https://doi.org/10.2760/759692.