Energy Research & Social Science 139 (2026) 104882

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Techno-economics and value judgments of modeling biochar production for carbon removal in climate change mitigation scenarios

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ARTICLE INFO

Keywords:
Carbon dioxide removal
Pyrogenic carbon capture and storage (PyCCS)
Integrated Assessment Modeling
Modeling transparency
Technological futures

ABSTRACT

Integrated assessment models (IAMs) create policy-relevant expectations about emerging technologies. Their modeling requires a stylized representation of many possible technological futures, which involves value judgments. Acknowledging calls for reflection on value-laden assumptions, we jointly present the techno-economic considerations and value judgments in modeling biochar production and its use for carbon removal in the IAM REMIND. Our framework distinguishes between the selection of technology configurations and their parameterization. For biochar, we first introduce a classification of production configurations into artisanal, mobile, established, and advanced industrial categories. In selecting biochar configurations, value judgments are embedded in assumptions of equivalence and fungibility with other mitigation options, given the socio-political and carbon permanence differences between them. Modelers also have to decide whether to include established or more advanced configurations that deliver greater systemic value but are associated with higher uncertainty. For parameterization, our data collection shows a wide range of quotable assumptions, providing scope for different levels of optimism. We then test the impact of cautious versus optimistic biochar production assumptions on biochar deployment in scenarios limiting climate change to low overshoot above 1.5 °C. The primary determinant of deployment is not the parameterization of biochar production, but rather assumptions about geologic CO_2 storage, which constrain the deployment of competing BECCS technologies. Nonetheless, biochar parameterization and the inclusion of an advanced, currently non-existent, configuration also influence deployment. The analysis highlights how technological framing and assumptions shape modeled technology potentials, underscoring the need for transparent and reflexive modeling practices.

1. Introduction

Process-based Integrated Assessment Models (IAMs) comprehensively represent processes and greenhouse gas mitigation options in the energy-economy-land-climate system. They are used to inform decision-making on climate change mitigation policy through mitigation scenarios [1]. In the models, the real-world diversity of technologies must be reduced to simplified and abstracted representations that capture their central dynamics [2]. The representation of carbon dioxide removal (CDR) approaches has received particular scrutiny [3,4]. To better reflect the variety of CDR options, the modeled CDR portfolio is being expanded beyond re- and afforestation, bioenergy with carbon capture and storage (BECCS) and direct air carbon capture with storage (DACCS) [1,5,6]. Pyrogenic carbon capture and storage (PyCCS [7]), i.e., the production of biochar and its non-oxidative use, is the most studied and currently most deployed novel CDR approach [8,9]. It has only recently been integrated into some IAMs, represented as a single production set-up [10,11], despite a large diversity of deployed and imagined configurations [12].

The fundamental technological process for producing biochar is pyrolysis of biomass, i.e., thermal conversion in the absence of molecular oxygen, which additionally yields gaseous and liquid products (pyro-gas and bio-oil). The production set-up can take many forms, from artisanal kilns to industrial plants with different co-products derived

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https://doi.org/10.1016/j.erss.2026.104882
Received 29 January 2026; Received in revised form 17 July 2026; Accepted 22 July 2026
Available online 14 August 2026

from the pyro-gas and bio-oil [7,13]. Biochar also has different non-oxidative applications that enable long-term carbon storage, including use in soil with agronomic and environmental benefits [1,14], in construction [15,16] and in composite materials [17]. Accordingly, promises about PyCCS' CDR potential and co-benefits are high [18], but there is also caution against techno-optimism and hype [19,20].

While dedicated techno-economic studies focus on individual configurations, locations, and points in time, IAMs can assess the techno-economic competitiveness of biochar production as part of the changing energy-economy-land system in pathways consistent with the Paris Agreement goals. This contributes to understanding PyCCS' large-scale mitigation potential in comparison to other CDR approaches. Given the variety of production, from smallholder cookstoves to industrial plants co-producing different energy carriers, its representation in IAMs is, however, not self-evident. Modelers thus have to make judgments about which approaches to represent. These choices are not purely objective but are influenced by personal or societal values and beliefs as well as practical reasons, like data availability or the model's spatial resolution [3,21].

The modeling choices for individual technologies matter because IAMs have performative political power. Scenario literature can play an important role in shaping expectations that emerging technologies will be cost-effective and in mobilizing resources for their implementation [22,23]. Given their authority in IPCC reports, IAMs have been powerful in making CDR relevant for climate politics [24]. This also matters for PyCCS, as the IPCC's 6th Assessment Report called for its inclusion in IAMs [1]. Its representation in IAMs can thus be expected to receive scientific and political attention.

Criticism of other CDR technology modeling has concluded that technological assumptions were too optimistic, that modeling was opportunistic, and that constraints beyond techno-economic feasibility were neglected [4,25,26]. However, IAMs have also been found to be too pessimistic about emerging technologies like photovoltaics [27,28] and to fail to keep up with real-world advancements [29]. In addition to practical factors, such as cognitive constraints and the resource intensiveness of updating parameterization, value judgments also shape technology representation. Critical literature on IAMs and the prominence of CDR in scenarios has primarily focused on value judgments in structural model assumptions, such as discount rates, perfect foresight, and the limited representation of governance and sustainability concerns [23]. Some of these, like assumptions about bioenergy supply and future cost reductions, directly relate to technology implementation. However, value judgments across the wide range of technology-specific assumptions are rarely discussed [3], and transparency efforts have focused on making data and code available rather than providing justifications and explaining tradeoffs [30,31].

In response to calls for reflection on modeling choices [30,32], we discuss the integration of biochar production in the IAM REMIND [33,34] to identify value judgments across multiple levels of assumptions. We present a framework to relate techno-economic considerations and value judgments in the technology modeling process. Through the analysis of a specific technology implementation, we thereby link modeling practice, critical scholarship and techno-economic literature, clarifying how technologies are abstracted in models, where key assumptions enter, and how techno-economic, ethical and epistemic considerations interact in practice.

Section 2 introduces the framework, which distinguishes the steps of (i) selecting technology configurations and (ii) selecting their parameter assumptions. In addition, biochar production and the REMIND model are introduced. Sections 3 and 4 analyze the decisions in each modeling step for the addition of biochar production to REMIND. Section 5 illustrates how optimism about biochar assumptions influences the modeled deployment in ambitious global climate change mitigation scenarios. Because other model and scenario assumptions also shape bioenergy technology deployment [35] and carry value judgments [3], we test the effects of biochar-specific assumption variation against different background scenario conditions.

Beyond providing an inside perspective on trade-offs in the modeling of emerging technologies, the paper offers a classification of biochar production configurations, a techno-economic data collection to situate parameterization in modeling and bottom-up studies, and insights into the global techno-economic potentials of PyCCS. These contributions help structure the growing body of claims about biochar and inform its continued integration into IAMs.

2. Technology modeling in IAMs and REMIND

2.1. A framework to approach technology modeling

Building on literature addressing the practice and implications of IAM modeling choices, specifically regarding CDR [2,3,21,23,24,31], and drawing on our experience implementing CDR methods in REMIND, we developed a framework to guide the analysis of the biochar modeling decisions in Sections 3 and 4 (Table 1).

Technology implementation includes two steps. First, IAM modelers **(i) select which configurations to represent**. Specifying configurations breaks down umbrella terms like BECCS or biochar into specific technological processes. Configurations can be included as default, made available for exploration, or excluded. Second, modelers **(ii) assign parameter values** for the selected configurations, which we refer to as parameterization. For most parameters, there is no single correct choice; instead, parameterization reflects interpretations of heterogeneous evidence and technology narratives [31]. For uncertain parameters, modelers should test the impact of varying assumptions on the modeling results. For parameters with a strong influence, it is common to define assumption sets (e.g., pessimistic, best guess, optimistic) that can be varied with scenario narratives.

In both steps, decisions are shaped by three interconnected

Table 1
Two implementation steps and three dimensions of considerations of the modeling process.

		Modeling steps	
		(i) Configuration selection (Section 3)	(ii) Selection of parameter assumptions (parameterization) (Section 4)
Consideration dimensions	(1) Technology manifestations & techno-economic evidence: What *could* be modeled?	Taking stock of possible configurations, understanding their features and narratives.	Collection of techno-economic data for parameterization.
	(2) Fit with the model framework: What *can* be modeled?	Which configuration features can be represented?	How does the techno-economic data relate to existing technologies?
		What practical constraints arise from computational capacity, human resources, project requirements, etc.?	
	(3) Ethical & epistemic considerations: What *should* be modeled?	How "equivalent" are the technologies to other mitigation options in the model? What are the consequences of ignoring inequivalences?	–
		What are the distributional consequences of selecting certain configurations or techno-economic assumptions?	
		Which uncertainties are considered acceptable, and how are they dealt with?	

dimensions of considerations: modelers must relate (1) the technological possibilities and associated narratives to (2) the constraints of their modeling framework while (3) engaging with ethical and epistemic considerations. The dimensions' relevance and specific implications depend on the modeling step and technology.

The first dimension covers what *could* be modeled by collecting and understanding **existing technology manifestations and techno-economic evidence.** For ***configuration selection***, taking stock of technological developments defines the possible configurations. In the case of biochar, the challenge lies in deriving plausible versions from unharmonized techno-economic literature on many configurations at varying maturity stages. Interpreting the configurations requires understanding technology narratives, which contextualize the technologies' role and promises within the climate-economy-land-use system. Different technology narratives can explain widely varying technology representation [31]. PyCCS, for example, could be framed as a small-scale, local soil improvement measure, or as a large-scale industrial technology to support the decarbonization of construction. Such narratives not only affect its maximum deployment, but also the choice of production conditions, like costs and energy co-production. For ***parameterization***, modelers also need to take stock of available techno-economic data [31], referring to databases (e.g., [36]) or assembling evidence from disparate sources [37]. The data collection provides a range of values that could be chosen and referenced.

Second, the **model framework** influences what *can* be modeled, considering the existing model structure and model narrative [31], as well as practical factors such as project objectives and computational and human resource constraints [21]. For ***configuration selection***, the questions are which and how many configurations can be covered. Representing multiple configurations increases computation time and data requirements, which also need to be kept up to date [29]. The model framework should also allow for an adequate representation of the technologies' main features. Otherwise, the errors from inadequately modeling a configuration may exceed those from excluding it. For ***parameterization***, technology competitiveness depends on relative, not absolute, costs and efficiencies [38]. The collected evidence must therefore be interpreted in the context of the model structure and other technology assumptions to reflect the intended narratives [31].

The effort spent on techno-economic data collection must balance scientific rigor with time opportunity costs. Similarly, the number of configurations represented is influenced by practical constraints, but also by epistemic values, like accuracy, that need to be weighed against simplicity and the ability to interpret results [2]. This illustrates that evaluating the techno-economic evidence, narratives, and their fit with the model framework involves **ethical and epistemic considerations**, whether explicitly or implicitly. This includes assessing distributional implications, political impacts, or epistemic values [2,39]. Below, we introduce two considerations that are particularly relevant to PyCCS and other CDR approaches.

Due to the uncertainties of emerging technologies, modelers have to weigh the consequences of being wrong [3]. Hollnaicher [3] argues that an optimistic representation of CDR approaches is ethically questionable, as it allows for shifting mitigation to the future and thereby transfers the burdens and risks of mitigation to future and more vulnerable populations. Similarly, Lenzi [40] identifies an epistemic uncertainty objection that it is “ethically unacceptable to gamble on technologies that are currently unproven, especially when the risks associated are great”. When adding a single technology to an existing model framework, we argue that the assessment of techno-optimism should also be relative to the representation of existing technologies to avoid biases. Otherwise, mitigation may be shifted to more uncertain or less sustainable options. Modelers must therefore evaluate the internal and external implications of more or less optimistic configurations and parameter choices.

Both configurations and parameterization decisions shape how technologies compete across time and space, embedding inter- and intragenerational distributional effects within the model [3,23]. Because IAMs seek to derive cost-optimal mitigation pathways, a ton of CO_2 avoided or removed is typically treated as equivalent regardless of its source or location. This reflects the physical property of CO_2 as a well-mixed greenhouse gas in the atmosphere, whereby its climate impact depends primarily on the globally accumulated stock of emissions. However, this notion is challenged by a broader understanding of equivalence, highlighting important differences related to the type and quality of CO_2 sources and sinks (e.g., their fossil or biogenic origin, or permanence), the geographic context (e.g., socio-political differences and structural inequalities), and the timing of emission and removal [41]. Such inequivalences could, for example, be represented in the scenario design, e.g., by pricing removal and emissions differently [42] or assigning a lower price to non-permanent CDR [43].

Before applying the structure of this framework to the selection of biochar production configurations (Section 3) and the parameter values (Section 4), we give an overview of biochar production and REMIND.

2.2. Biochar production and application

Fig. 1 summarizes the integral and optional inputs, conversion elements, and outputs of biochar production configurations. Biochar is produced through pyrolysis, the heating of biomass in the absence of molecular oxygen. In addition to biochar, pyrolysis yields a low-grade synthesis gas (pyro-gas) and a tarry liquid (bio-oil). The product yields and properties depend on the feedstock and pyrolysis conditions [7]. As slower heating rates favor biochar production, slow pyrolysis is typically used for PyCCS [44].

The amount of carbon permanently sequestered depends on both the biochar yield and the fraction of its carbon that is persistent. Pyrolysis temperatures range from 300 to 900 °C. While higher pyrolysis temperatures reduce biochar yield, they enhance aromatization and hence the stability of the carbon [45–47] (see the SI for details).

The pyro-gas and bio-oil can also be utilized, typically via combustion for heat and power. There is thus a trade-off: lower pyrolysis temperatures result in higher biochar yields, whereas higher temperatures yield less biochar but achieve a higher carbon persistence and higher energy yields [7]. The CO_2 emitted during combustion, as well as the bio-oil, can also be captured and stored geologically for additional carbon removal.

The primary input is biomass feedstock, including agricultural and forestry residues, purpose-grown biomass, digestate, or sewage sludge [48,56]. This paper focuses on lignocellulosic biomass. Often, only residues are investigated as feedstocks [49,50], but dedicated crops may be required for larger deployment due to limited availability of residues and competition for their use [45]. In addition, electricity and heat may be required to dry the feedstock and to start and sustain the pyrolysis. This energy requirement is often covered by part of the co-product combustion [51].

The set-up of the elements in Fig. 1 varies, and not all features can be realized in one configuration: Simple pyrolysis kilns produce only biochar [52], while automated systems range in scale and co-product use. Small-scale systems located close to feedstocks reduce transport costs but typically have a higher capital cost intensity [53], whereas larger systems more efficiently co-produce energy. Section 3 presents plausible configurations.

Finally, permanent CDR requires a non-oxidative use of the biochar. The predominant application is in agriculture, with beneficial effects including enhanced crop yields and improved water or nutrient use efficiencies [14]. However, it can also be used in construction, for instance for asphalt [15] and concrete [16], or in polymer composites [17]. The biochar product thus has a material value, contributing to the overall technology profitability.

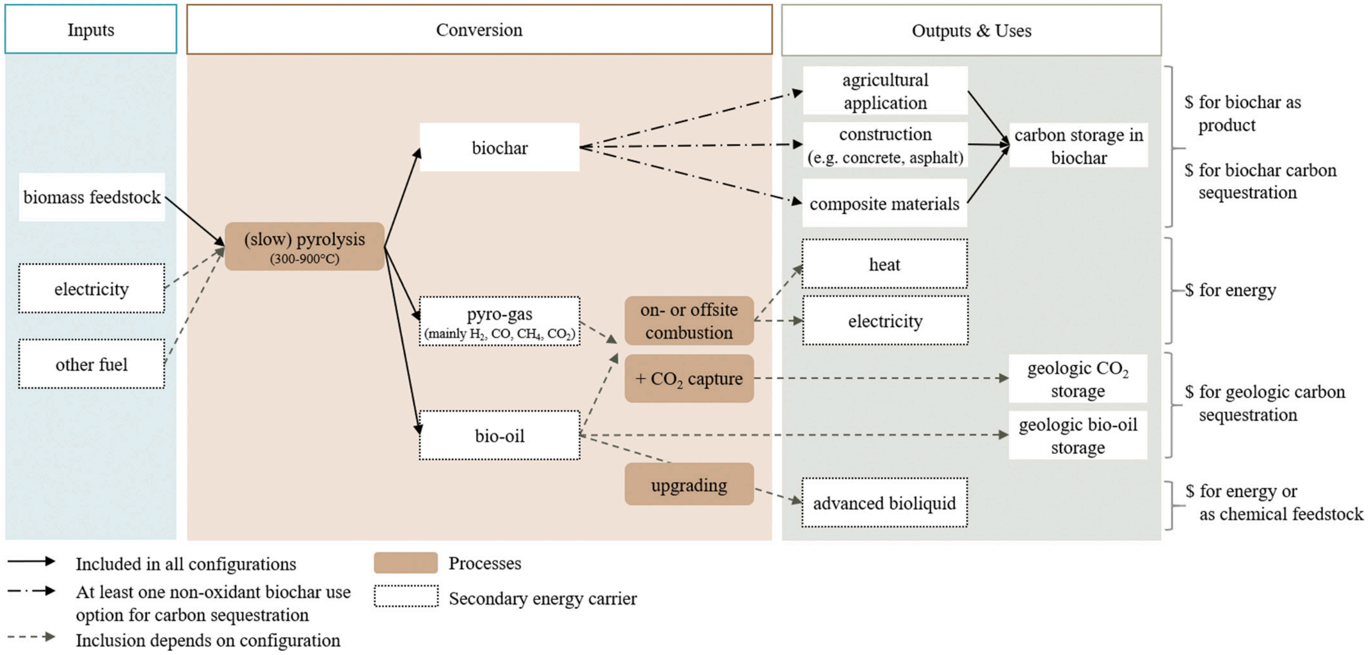

Fig. 1. Schematic overview of PyCCS elements that are integral (black lines) or included only for certain configurations (dashed grey lines). Different revenue streams are generated, depending on outputs and their uses. In addition, pyrolysis can be integrated into other bioenergy plants, e.g., providing heat to a bioliquid plant for feedstock drying (see Section 3).

2.3. REMIND

REMIND [33,34] is a detailed global energy–economy–climate model representing twelve world regions. It is used to identify cost-effective transformation pathways to reach global or regional climate targets. It optimizes intertemporal investment and interregional trade by maximizing welfare in a Ramsey-type growth model, where welfare depends on consumption. REMIND comprehensively covers the energy supply chain (primary energy extraction, conversion into secondary energy carriers, and provision of final energy) and energy demand from the buildings, industry, and transport sectors [33].

REMIND determines the cost-optimal technology mix to supply energy to the demand sectors, while adhering to resource availability constraints and climate targets. Technology competitiveness is thus shaped by the relative technology costs, efficiencies, and endogenous energy carrier prices, under the given constraints.

The main mechanism to achieve climate targets is the adjustment of the carbon price. It changes the competitiveness of technologies by pricing their emissions or rewarding the removals they provide. IAMs analyzing global cost-effective mitigation typically apply a globally uniform carbon price to represent full international cooperation. Although other approaches are possible, we use this uniform pricing as the reference case for the implementation of biochar.

The energy supply sector is represented in high detail, including more than 50 technologies. Technologies are modeled as conversion processes transforming one energy carrier into another. They are characterized through techno-economic parameters that jointly determine their competitiveness (Table S1). These include fixed and variable operating costs, capital costs per unit of installed capacity, capacity utilization rate, and operational lifetime. Capital costs may decrease with deployment due to learning effects. Conversion efficiencies define the energy yields per unit of input, along with associated emissions or removals. Feedstock and energy prices are determined endogenously depending on the system's demand and supply.

The available CDR technologies include DACCS, ocean alkalinity enhancement, enhanced weathering, and multiple BECCS configurations, converting biomass into electricity, methane, hydrogen, or advanced bioliquids. Bioliquids are particularly valuable to the system because they can be used as fuel or feedstock in hard-to-electrify sectors and the chemical industry [54]. The BECCS options are also available without CO_2 capture, and biomass can additionally be transformed into heat and power.

PyCCS is similar to BECCS from an energy system perspective because it converts biomass and provides carbon removal and often energy. PyCCS' competitiveness in the model thus depends on its comparison with BECCS technologies in terms of their carbon removal and energy efficiencies, the value of energy carriers to the system, and production costs.

Generally, PyCCS has a lower carbon removal efficiency than comparable BECCS systems. The removal rate is lower because a fraction of the carbon remains in the pyro-gas and bio-oil, unless these are additionally captured and stored. Additionally, the biochar carbon permanence is lower than the permanence of geologic CO_2 sequestration [7]. However, PyCCS' independence from geologic storage infrastructure is an advantage. PyCCS' energy yields are lower, because some biomass enthalpy is contained in the biochar [55]. However, pyrolysis units can utilize a wide range of biomass [56] and be built at smaller scales, potentially reducing feedstock sourcing costs. They are often technologically less complex, facilitating application in different contexts and resulting in lower costs [57]. Finally, the biochar's material value is a unique feature of PyCCS.

Although REMIND covers all relevant greenhouse gas-emitting sectors, it has to be coupled to the global land-use model MAgPIE for a detailed representation of the land use sector [58]. For standalone analyses, exogenous land-based emission pathways, including afforestation, and biomass supply curves are derived from MAgPIE. For modeling biochar, the representation of land-use in MAgPIE thus prevents a detailed modeling of biochar application in agriculture, challenging the representation of the biochar's material value in standalone REMIND.

3. Classification and selection of biochar production configuration

To structure the selection of individual biochar production processes, we classify technology configurations based on characteristics related to techno-economic uncertainty and energy system competitiveness; taking stock of what *could* be implemented. The stylized configurations presented in Table 2 are derived from scientific literature and industry communications, but do not claim to be exhaustive.

The classification's first tier distinguishes between artisanal, mobile and industrial production.

- Small-scale *artisanal production* is characterized by simple equipment such as kilns, pits, or pyrolytic cookstoves, primarily used by smallholders, households, small businesses, or cooperatives in developing regions [18]. They have little to no capital costs but high labor intensity. Biochar is typically used on-site in agriculture. Documentation, reporting, and verification can be done via mobile phone apps [59], and a specific artisanal biochar certification standard exists [60]. The CDR potential is up to 1.2 Gt CO_2 yr^{-1} [61], indicating relevance for model integration.
- *Industrial production* is characterized by automated machinery and higher capital intensity.
  - o *Established production* configurations dominate the emerging biochar market [56]. The pyro-gas and bio-oil are either not used beyond the sustenance of the pyrolysis plant [62] or converted to heat and power.
  - o *Advanced production* configurations are at a lower maturity stage, but feature improvements that could increase the competitiveness of PyCCS. To increase carbon removal efficiency, a CO_2 capture unit can be added to larger plants [56,63] or the bio-oil can be stored geologically or used in durable products [7]. To increase the energy co-product's value, the production of advanced bioliquids appears most promising, as these can be used in hard-to-electrify sectors as fuels or basic chemicals [54]. Various types of advanced bioliquids could be produced through different routes, e.g., through fast pyrolysis with bio-oil upgrading [64] or the integration of slow pyrolysis into gasification with Fischer-Tropsch synthesis plants [65]. Other configurations, like upgrading to gaseous biofuels [44], are possible, but are not investigated here due to their lower literature prevalence and model relevance.
- *Mobile production* is an intermediate category, using small-scale machinery that has a higher labor intensity. The mobility facilitates access to highly decentralized feedstocks [66], yet mostly prevents energy co-production.

The following Sections 3.1 and 3.2 detail the influence of the model framework and ethical and epistemic considerations for including artisanal and industrial configurations. Mobile production is not further covered due to limited potential and lack of sufficiently detailed feedstock representation in REMIND.

3.1. Artisanal production: context-specificity and extended equivalence considerations

Artisanal biochar production is promoted as a multiple-win solution due to its simplicity and potential benefits for soils, yields, incomes, and climate resilience in low-income regions [18,57]. However, its feasibility and outcomes are highly context-dependent, shaped by financial, labor, and knowledge constraints and by the cultural fit with existing cooking and farming practices [67–69]. In particular, local agricultural impacts and the availability of and competition for biomass residues are key context-specific factors determining its feasibility [70,71].

Modeling should capture these two main driving factors. In REMIND, however, the low spatial resolution leads to a coarse representation of traditional biomass uses, limiting the ability to reflect the relevant biomass use dynamics. Because soil application effects also cannot be explicitly modeled (see Section 2.3), integration into regional and global carbon markets would be the only endogenously modeled incentive in REMIND through the carbon price.

This has a normative implication through the assumption of equivalence and fungibility of artisanal biochar and other mitigation options. Incentivization through the carbon price would align with the standard approach to treat each ton of CO_2 as interchangeable due to its climatic effect. However, this would overlook important socio-political and geographical differences compared to mitigation in industrial contexts [41]. In particular, it risks framing removals in less affluent regions as substitutes for mitigation elsewhere. Deciding to what degree artisanal biochar should be treated as equivalent to other mitigation options by applying the carbon price – or to use alternative incentive mechanisms – is a value judgment with consequences for the interregional distribution of the mitigation burden in the model.

Given the limited ability to represent biomass and agricultural dynamics in REMIND, we consider the exclusion of artisanal biochar production preferable to its inadequate representation, as misrepresentation would be more misleading than omission.

Table 2
Classification of stylized biochar production configurations from an energy system modeling perspective. DM = dry matter biomass input.

Category	Artisanal production		Mobile production	Industrial production					
Configuration	Pits, kilns etc.	Pyrolytic cookstoves	Mobile pyrolysis units	Established (predominant in the emerging market)			Advanced (improved carbon or energy use)		
				No co-products	Offsite bio-oil use	Onsite heat & power generation	Advanced bioliquids	CO_2 capture & storage	Bio-oil storage
Co-product use	None	Heat	None	None	Bio-oil for offsite heating	Heat or heat-and-power	Advanced bioliquids	Various combinations of co-product use possible, e.g. heat-and-power	
Prioritized output	Biochar		Biochar	Biochar		Biochar or energy	Biochar or bioliquid	Carbon removal[a]	
Production scale	Typically <~120 t DM yr^{-1}; up to 1800 t DM yr^{-1}	<1 t DM yr^{-1}	Mobile, <1000 t DM yr^{-1}	Typically 2000–5000 t DM yr^{-1}, but up to 25,000 t DM yr^{-1}			>5000 t DM yr^{-1}		
Who & where	Smallholders, households, small businesses or cooperatives in developing regions	Households in developing regions	Actors with access to capital, decentralized biomass and wastes, and local uses for biochar	Actors with capital access, local biomass availability, and local uses for biochar		Industrial or district heating contexts	Industrial contexts		
Current deployment	Development projects/commercial		Commercially available	Commercially available			Research/single commercial projects		

[a] Sum of carbon in biochar and the CO_2 captured and sequestered or carbon stored via bio-oil

3.2. Industrial configurations: weighing status quo confidence and future attractiveness

Implementing industrial configurations involves a trade-off between higher confidence in the technological feasibility of established configurations and the presumably higher long-term potential of the advanced configurations. The underlying question is: how optimistic *should* PyCCS futures be envisioned by default and in exploratory analysis? The established configurations are already being deployed, justifying their default implementation. At a large deployment scale, however, they may have limited value in a decarbonizing energy system, for two reasons. First, the energy co-products heat and power are less competitive in deep decarbonization pathways compared to hydrocarbon production that is required for hard-to-electrify sectors [54]. While bioenergy technologies producing heat and power have a role, e.g., for balancing wind and solar power variability [72], there are other cost-effective alternatives for fossil-free heat and power production. Second, among these bioenergy technologies, the established PyCCS configurations have a competitiveness disadvantage due to both lower energy and lower removal efficiencies than those of the comparable BECCS configurations [55]. Because the advanced PyCCS configurations improve the energy or removal performance, the established options may not be the most relevant long-term configurations. Excluding the more advanced yet non-deployed configurations may thus underestimate the future relevance of PyCCS and may be interpreted as closing down relevant technological futures. Therefore, we evaluate the additional inclusion of advanced configurations individually in the following, assessing the level of uncertainty of their techno-economic evidence and their fit with the model framework.

The *configuration including geologic bio-oil storage* is subject to multiple techno-economic and legal uncertainties. Details such as the bio-oil's storage costs are lacking in the literature to our knowledge. The IAM GCAM adopts a stylized implementation, assuming sequestration of an unspecified fraction of the bio-oil without modeling its handling and costs [10]. Such an approach increases the amount of carbon removed per ton of biomass without accounting for the techno-economic requirements from the bio-oil storage. In addition, the fit of geologic bio-oil storage with legal frameworks outside the USA is unclear, as it differs legally and technologically from CO_2 storage, touching waste and mining regulations. Given these uncertainties, we judge that, for REMIND, introducing a bio-oil storage configuration with higher removal efficiency cannot be sufficiently substantiated at this stage.

Configurations that include CO_2 capture units effectively transform established biochar systems into BECCS options. Their techno-economic uncertainties are therefore comparable to those of the BECCS technologies that are already represented in the model. The key issue is thus not uncertainty, but whether the model framework can adequately capture the features that distinguish these biochar configurations from the modeled BECCS options: Because these biochar configurations also rely on CO_2 infrastructure for part of their removal while generating less heat or power, the material value from biochar application becomes its main distinguishing feature. An adequate implementation of this configuration therefore requires a detailed representation of biochar application. As agricultural application cannot be explicitly represented in REMIND (see Section 2.3), this configuration is not included for practical reasons.

Including a biochar *configuration that co-produces advanced bioliquids* appears particularly promising, given the value of bioliquids for mitigation of hard-to-electrify sectors [54]. Similar bioenergy technologies are already represented in REMIND. The model's predominant route for converting lignocellulosic biomass to bioliquids is gasification with Fischer-Tropsch synthesis. In its BECCS variant, the carbon capture efficiency amounts to only 41% of feedstock carbon, because part of the feedstock carbon is contained in the bioliquid. A biochar configuration co-producing advanced bioliquids could achieve a comparable carbon removal efficiency. Sufficient techno-economic data for implementation in REMIND could be derived from the literature (see Section 4). However, co-production of advanced bioliquids is not yet a standard biochar technology and remains the subject of research. We therefore consider it too uncertain for default implementation and only include it for exploratory analyses.

Hence, only *established* configurations are implemented as new default CDR technologies, reflecting their current market prevalence. A modeling choice is whether to prioritize completeness in representing their variety or to focus on few configurations. Industry perspectives in Europe suggest that the configuration co-producing only power has limited future relevance [56]. The European Biochar Certificate requires energy or material use of the pyrolysis co-products [73], with exemptions for production outside Europe [74]. However, many techno-economic studies analyze set-ups without energy co-production (see Section 4.2), and relevant co-production pathways may differ by region. Therefore, we opt for a comprehensive representation of four configurations: co-producing heat-only, power-only, heat and power, or no energy.

Table 3 summarizes the main decisions about the configurations selected for REMIND and the respective value judgments and techno-economic considerations.

4. Navigating possible parameterization assumptions

To identify the values that *could* be used for parameter assumptions, we collected biochar production data for lignocellulosic feedstocks. We employed a non-systematic approach to identify academic papers, combining keyword searches, snowballing, and studies sourced from two systematic reviews [70,75]. The collection additionally includes publicly available manufacturer information and aggregated data from European Biochar Certificate submissions [73]. Many of the identified sources did not provide sufficiently detailed information. The selected references each cover only a limited set of configurations and report parameters with differing scopes and units, requiring harmonization. For cost comparison, dry matter biomass feedstock is chosen as the base unit because pyrolysis temperature and feedstock characteristics influence biochar yields. All monetary values are in USD_{2015}. See the SI for details and underlying data.

The collection shows a wide range of possible cost and efficiency assumptions. Both current costs and efficiencies are thus open to interpretation [31]. This gives modelers considerable discretion in selecting values, depending on their views and the model context. In the following, we derive two sets of parameterizations that can be varied in scenario narratives: a cautious baseline and more optimistic assumptions for the established configurations. The baseline is more conservative to be consistent with the modeling framework, in which novel technologies are parametrized conservatively to avoid overreliance on CDR. However, the discussion shows that what constitutes "conservative" cannot be clearly defined. The assumptions summarized in Table 4 form the basis for exploring the relevance of parameterization optimism in the scenarios presented in Section 5.

4.1. Technological assumptions

For the four established configurations, a key choice concerns the pyrolysis temperature and the fraction of biochar carbon that is persistent for at least 100 years. As described in Section 2.2, lower temperatures increase biochar yield and its carbon content but decrease its persistence in soil. The elemental H:C ratio of biochar is the most widely used indicator of persistence, with different approaches translating it into a permanent carbon fraction (see the SI for details). Modelers thus need to decide which temperature should be considered sufficiently high and which permanence model should be applied.

For the *established configurations*, we use biochar yields and characteristics for woody feedstocks from Schmidt et al. [7] because of the high level of detail provided. We select a pyrolysis temperature of 500 °C to balance high biochar yield and high biochar persistence, indicated by an

Table 3
Considerations leading to exclusion and default or explorative inclusion of configurations in REMIND.

Category & configurations		Decision for REMIND	Techno-economic considerations	Value-laden considerations
Artisanal production		Not included	Context-specificity, particularly feedstock sourcing and biochar application benefits, cannot be adequately represented.	Socio-political and geographic (in)equivalences of artisanal biochar removals and industrial mitigation within and across regions.
Industrial production	Established	Default inclusion: - No energy co-production - Heat - Power - Heat and power	Different valuation of heat and power co-production in different regions. Systems have different complexity, thus different capital costs.	Comprehensive representation or simplicity. Weighing uncertainty vs. expected potential: currently dominating options may not be the most relevant configurations in the long term but advanced options are more uncertain.
	Advanced	Explorative inclusion: advanced bioliquid co-production	High value of bioliquids in the energy system. Competitiveness with comparable BECCS option through lack of CO_2 infrastructure requirement.	Sufficiency of techno-economic data availability.
		Not included: bio-oil storage; CO_2 capture	The material value of biochar is critical for competitiveness of the CO_2 storage option against comparable BECCS but cannot be adequately represented.	Techno-economic and legal uncertainties of bio-oil storage.

H:C ratio below 0.4. We further assume that 80% and optimistically 90% of the carbon in the biochar remains stable for at least 100 years, reflecting the central and 95% confidence interval estimates of the IPCC guidelines [76].

Additionally, assumptions on the net usable heat and power yields are required for the three co-producing configurations. In contrast to the immediate pyrolysis product yields, which are well described and largely consistent across studies (Fig. S1), these co-product yields vary widely, even within pyrolysis temperature groups (Fig. 2). Overall conversion losses range from 0% [77] to 60% [51], due to different technology assumptions (e.g., pyro-gas-to-power efficiencies) and system boundaries. For example, the heat demand for drying the feedstock depends on its moisture content.

Even the 450 to 650 °C range around the selected 500 °C provides substantial scope for more or less optimistic framing in the model. For our baseline assumption, we select the lowest yields for 450 to 650 °C processes in Fig. 2. For a more optimistic high-efficiency parameterization, estimates in the middle range of the data collection are chosen (Fig. 2). We refrain from choosing one of the upper estimates because these would be too optimistic compared to the assumptions for the existing bioenergy technologies in REMIND. For example, power yields for 550 °C and 650 °C pyrolysis systems in Woolf et al. [55] are higher than the assumed power yields for the dedicated biomass integrated gasification combined cycle technologies in REMIND. We keep biochar yields constant across all established configurations to allow a consistent analysis of the effects of varying energy yields in Section 5.

In addition to the biomass feedstock, we account for electricity used to operate the plant, assuming 2% of the bioenergy input [51]. Electricity consumption is accounted for in the net power yields of the power-only and heat-and-power configurations.

For the exploratory implementation of a bioliquid-producing route, we select a single parameterization. To explore the role of bioliquid co-production, we select a set-up that integrates slow pyrolysis with gasification and Fischer-Tropsch synthesis [44] because of its consistency with REMIND's reference technologies (see the SI for details).

4.2. Biochar production cost assumptions

The assumptions determining the production cost of PyCCS include capital, fixed and variable operating costs, feedstock costs, and electricity costs. Energy and biomass prices are endogenously determined. The remaining assumptions are discussed below and summarized in Tables 4 and S2.

For the four established configurations, not only the total cost, but also the distribution of costs across capital, fixed, and operating cost components differs widely (Fig. S3). Therefore, we prioritize consistency with other REMIND technologies for operational costs and add additional costs for the handling of biochar [66] (see the SI for details).

For *capital costs*, the data collected for the established configurations in Fig. 3a and b differ by a factor of four. We selected capital costs such that they increase with biochar configuration complexity, such that they present a medium to high estimate in the literature, and that capital costs for biochar production are comparable to those of the biomass integrated gasification combined cycle technology in REMIND [79]. For the baseline "high" cost assumptions, we use data from Sessions et al. [80] as an anchor, which provide costs for power and no-co-product options. Even though the costs from [80] are overall in the medium range of the collected data, they exceed some high estimates from sources providing high and low assumptions. Further, these costs are slightly lower than those of the comparable bioenergy technologies in REMIND (Fig. 3a). This may nonetheless appear to be an optimistic choice. However, the costs from Roberts et al. [81], which lie at the lower end of capital costs, are frequently used, also informing the main estimate in another IAM [10].

For the more optimistic case, we implement endogenous cost reductions, reflecting the expectation that costs decrease with cumulative

Table 4
Variation of key biochar production assumptions for REMIND. Full parameter set in Table S2. In the optimistic case, capital costs can decrease from the baseline to the low floor costs through learning. For the configuration co-producing both heat and power, the respective energy carrier yields are separated by a semicolon.

	Biochar yield	Co-product yields		Capital costs	
		Low (baseline)	High (optimistic)	Low (optimistic floor costs)	High (baseline)
Configuration	[MJ biochar/MJ feedstock]	[MJ energy/MJ feedstock]		[USD_{2015}/t dry matter feedstock yr^{-1}]	
No co-product	0.48	–	–	140	296
Heat	0.48	0.28	0.35	183	392
Power	0.48	0.06	0.18	217	426
Heat and power	0.48	0.13; 0.05	0.21; 0.10	271	479
Bioliquid	0.36	0.38	–	–	655

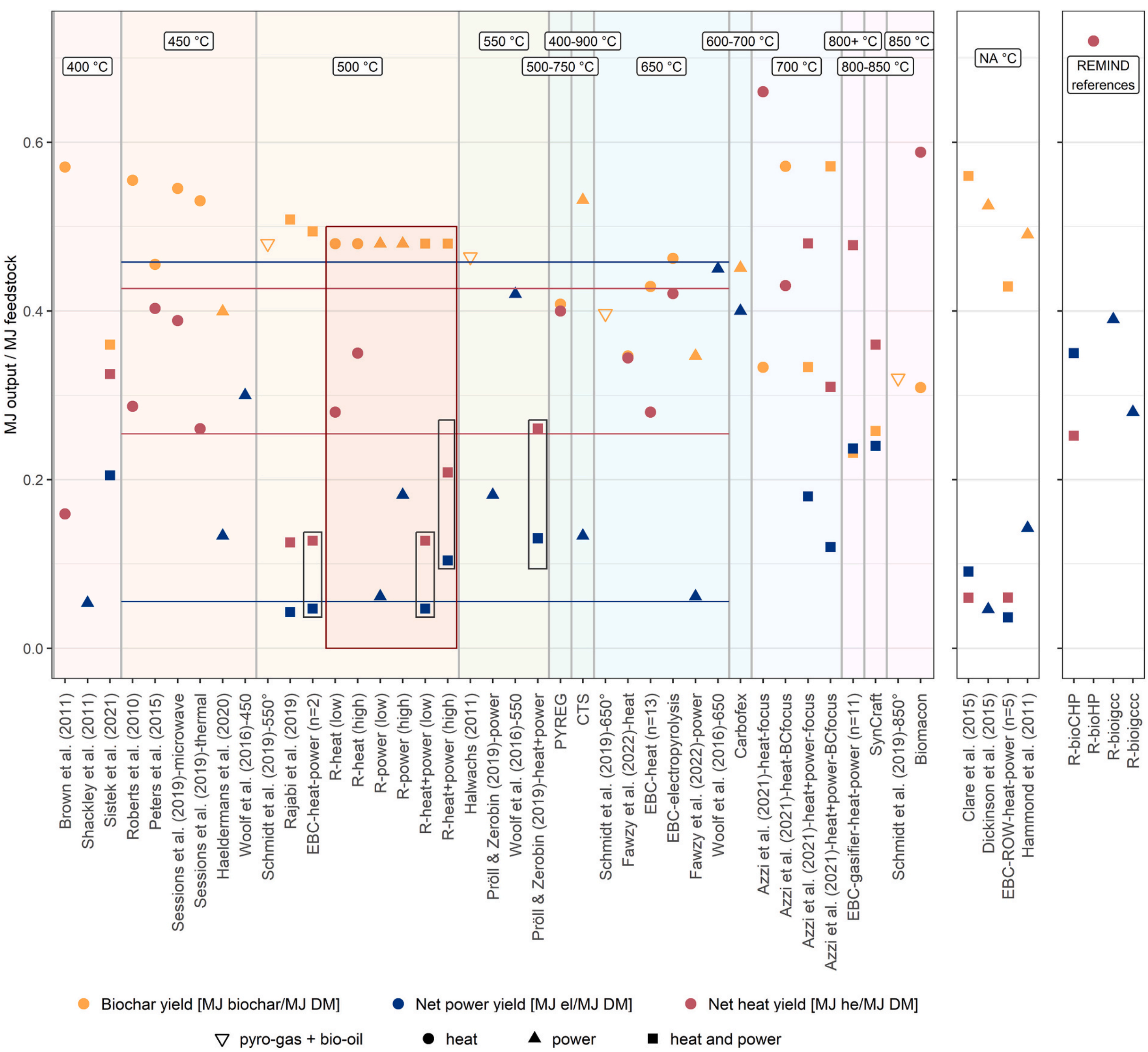

Fig. 2. Biochar and energy co-product yields (MJ output per MJ feedstock) for established configurations co-producing heat (circle), power (upward triangle), or both (square) as well as data points without specification of bio-oil and pyro-gas use (downward triangle). Entries are ordered by pyrolysis temperature, indicated at the top. Studies that do not report a pyrolysis temperature are categorized as NA °C. The selected high and low assumptions are highlighted by the red box. For comparison against the data collection, horizontal lines indicate the range of efficiencies for heat-only and power-only configurations with pyrolysis from 450 to 650 °C. The references used for heat-and-power are highlighted by black boxes. For comparison against other bioenergy technologies in REMIND, energy efficiencies from bioenergy heat production (R-bioHP), combined heat and power (R-bioCHP), and biomass integrated gasification combined cycle without (R-bioigcc) and with CO_2 capture (R-bioigccc) are provided on the right. CTS, Syncraft, Pyreg: suppliers for pyrolysis equipment, publicly available data. EBC: data from certification process according to the European Biochar Certificate [73] and Global Biochar C-Sink [78]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

deployment due to learning effects and serial production. The floor costs are given by the "low" data in Fig. 3a and b. Such learning effects are implemented in REMIND for technologies such as solar power, electrolysis, and direct air capture, but not for bioenergy technologies.

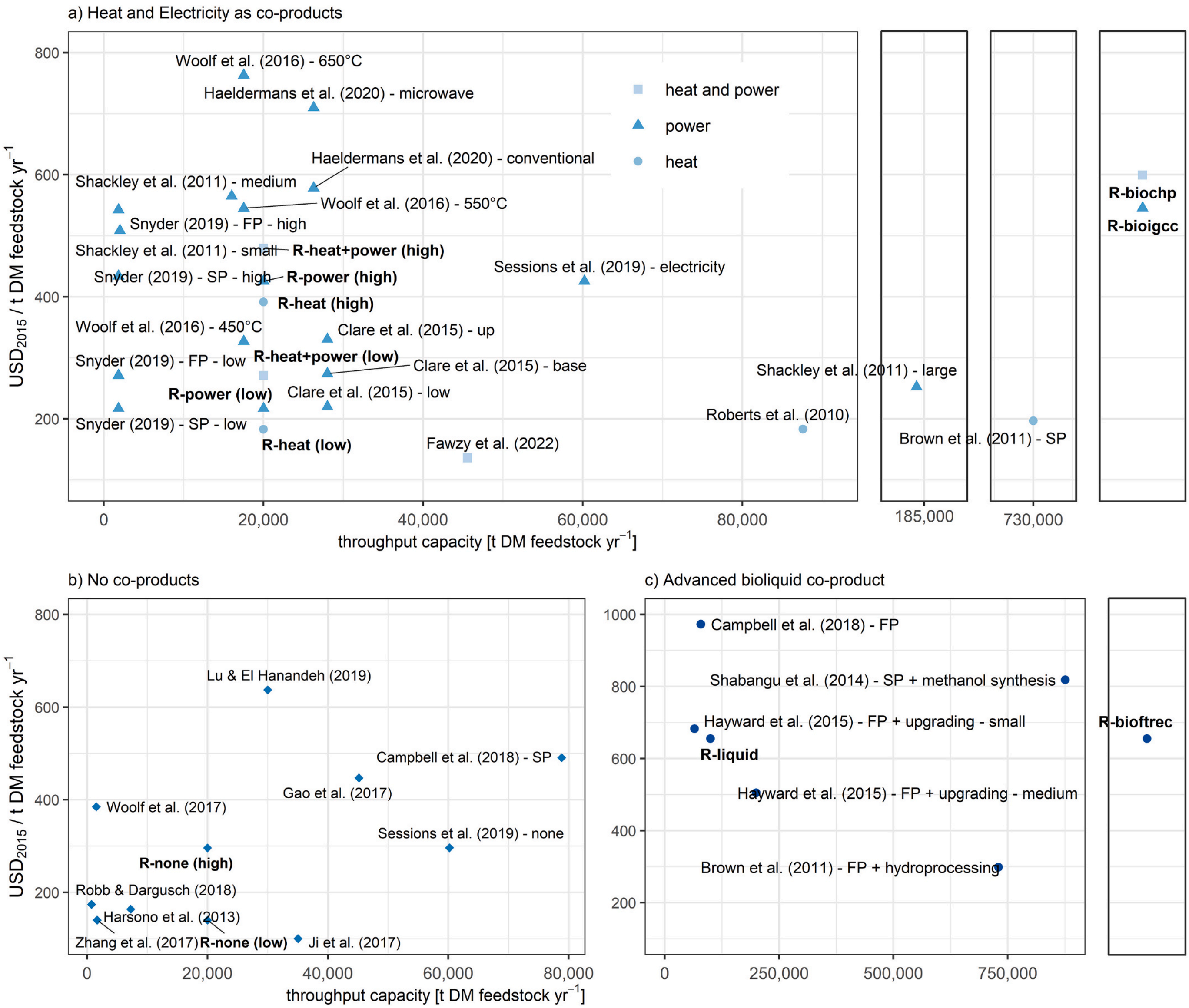

Fig. 3. Initial investment cost of biochar production configurations by co-product. Data refers to dry matter (DM) of maximum biomass throughput capacity per year. SP = slow pyrolysis, FP = fast pyrolysis.

Therefore, biochar technologies are not subject to endogenous learning in the baseline implementation.

Data collected for the bioliquid production route in Fig. 3c include capital costs that are both lower and higher than the assumptions for the comparable bioenergy configurations in REMIND. For the exploratory implementation, our best guess is that costs should be comparable to those of the system without CO_2 capture, essentially replacing the co-production of power with biochar. We add variable costs from Brown et al. [64] which are higher than those of the established biochar configurations and other bioenergy technologies.

4.3. Biochar application assumptions

The model incentive to deploy PyCCS is determined by the carbon price for removals, the value of the co-produced energy, and the material value of biochar application. The first two are endogenously determined in REMIND, but the material value of biochar use must be explicitly represented. The scope of applications considered is an important narrative component, influencing maximum deployment and thereby the inferred relevance of biochar.

The implementation in REMIND is affected by its limited land-use representation, preventing process-based modeling of biochar application in agriculture (see Section 2.3). Omitting the application value, however, would neglect a key feature of PyCCS. Alternatively, representing only its use in construction would ignore the dominant narrative of agricultural use. A demand function could reflect regional differences and heterogeneous application benefits, e.g., depending on soil types [14]. However, such research is not available, and its derivation would have exceeded the scope of this study.

We therefore adopt a simple but transparent approach, assigning the biochar product an exogenous value, similar to the approach in techno-economic studies [51,82]. This material value declines over time to reflect decreasing marginal value in high-deployment scenarios. Based on current biochar prices (Fig. S5), we assign 300 USD_{2015}/t biochar until 2025, declining to 70 USD_{2015}/t biochar by 2045 or 2050 under baseline and optimistic assumptions, respectively (Table S3).

This stylized representation implies that the types of application are not specified. It may inflate PyCCS deployment, for example if regulations are not adjusted to allow application in construction. However, we consider it necessary to have some representation of the material value because it is a main feature of PyCCS, and choose the exogenous values rather pessimistically. It is a compromise that may be criticized as opportunistic and optimistic [26]. To assess its influence on the modeling results, we conduct a robustness analysis where the application value is omitted in Section 5.3.

5. PyCCS deployment in REMIND under different biochar production assumptions and background conditions

In this section, we analyze the influence of optimism in parameterization and configuration assumptions on biochar deployment in REMIND and compare its effect to the influence of system-wide scenario background conditions. Note that value judgments that led to the exclusion of certain configurations in Section 3 cannot be explored in model results.

All scenarios limit cumulative CO_2 emissions to 650 Gt CO_2 from 2020 onwards, consistent with low overshoot of the global 1.5 °C target. They are based on default REMIND assumptions for the middle-of-the-road Shared Socioeconomic Pathway (SSP2, see also the SI). The scenarios include BECCS, DACCS, and biochar production variations. Land-use change emissions, including afforestation, are exogenous. A robustness analysis additionally includes ocean alkalinity enhancement and enhanced weathering.

Two background scenario conditions affecting the techno-economic potential of PyCCS and its competitiveness with BECCS are varied: biomass availability, because its limitation intensifies the competition for feedstocks between BECCS and PyCCS, and CO_2 storage availability, because its limitation increases the value of non-geologic storage of biogenic carbon in biochar. Applying these limitations yields four background conditions. Under *default* conditions, biomass is limited globally to 100 EJ yr^{-1} for sustainability reasons [83], and CO_2 storage is limited to ~20 Gt CO_2 yr^{-1} globally through an annual injection limit of 0.5% of the regions' storage capacity [6]. The other scenarios have stricter limits: 70 EJ yr^{-1} for bioenergy (*biomass limit*), ~4 Gt CO_2 yr^{-1} for geologic CO_2 storage (*storage limit*) to account for feasibility concerns [84], and a combination of both (*storage & biomass limit*).

For each of these background conditions, we compare scenarios with three biochar parameterization profiles for the established configurations with increasing optimism: the conservative *baseline* assumptions, a case with *lower cost*, and a very optimistic edge case with *lower cost and higher efficiencies* (Table 5). Sections 5.1 to 5.3 analyze the effects of background assumptions and biochar representation optimism on deployment. Section 5.4 explores the effect of including an advanced bioliquid configuration.

5.1. Biomass and geologic CO_2 storage assumptions dominate the PyCCS deployment scale

Fig. 4 presents PyCCS and other CDR deployment across the 12 scenarios combining the four background conditions and three parameterization variations, including only the established configurations selected in Section 3.2. Panel a) shows that global PyCCS deployment depends most strongly on the limitation of geologic CO_2 storage. Under *default* limits, PyCCS exceeds 100 Mt CO_2 yr^{-1} only in the most optimistic edge case parameterization, whereas it exceeds 500 Mt CO_2 yr^{-1} for all parameterizations in the geologic *storage limit* case. Fig. 4b shows that BECCS is reduced under the *storage limit*, and that this reduction is only partially offset by PyCCS.

When *only biomass* is constrained, BECCS deployment also declines compared to the *default*, while PyCCS remains similar, and some DACCS is deployed (Fig. 4b). Under *biomass and storage limits*, however, PyCCS exceeds 250 Mt CO_2 yr^{-1} despite the biomass limit, because alternative carbon storage gains importance. Compared to the *storage limit* conditions, BECCS is deployed to a similar extent, and only PyCCS decreases due to the biomass limit (Fig. 4b), driven by the higher efficiencies of BECCS. This pattern is robust to the inclusion of additional CDR technologies (Fig. S6).

The deployment of PyCCS is thus shaped not only by value judgments in the technology-specific assumptions, but also by those in the background conditions: The primary driver of PyCCS competitiveness in the model is the assumed availability of geologic storage. Geologic storage is subject to large uncertainties, and its stylized representation in IAMs has been criticized for insufficiently accounting for scale-up challenges [84]. PyCCS deployment also depends on biomass supply assumptions, which have been highlighted as overly optimistic in other analyses and as introducing normative biases for the model deployment of BECCS [23].

Beyond the assumption of yield increases, the stylized biomass supply representation also includes a lack of feedstock differentiation. This led to the exclusion of mobile biochar production, but it also means that the feedstock access advantages of the smaller established configurations over centralized BECCS cannot be represented. For example, pyrolysis can process very low-quality biomass that is generally considered waste, thus potentially constituting a disposal service. This shortcoming may lead to an underestimation of PyCCS compared to BECCS and other bioenergy technologies in our scenarios.

5.2. The influence of parameterization optimism on PyCCS deployment

Within each background scenario condition, more optimistic assumptions about costs and efficiencies also substantially increase PyCCS deployment (Fig. 4a). This effect is most pronounced among scenarios limiting geologic storage. Lowering cost and increasing efficiencies each approximately double PyCCS deployment. Among the combined efficiency increases, higher carbon persistence has a stronger effect than higher energy efficiencies. The increase in PyCCS exceeds the direct effect of higher removal per unit of biomass in the robustness analysis (Fig. S8).

The parameterization optimism also affects the relative deployment of the different configurations. Fig. 4c shows the contribution of the four established configurations to PyCCS deployment in 2050. Across background scenarios and parameterizations, the heat-only configuration has one of the largest shares. The configuration without energy co-production is most deployed under the baseline parameterization, whereas the share of the heat-and-power and power-only set-ups increases most strongly through more optimistic energy efficiency assumptions. Parameterization optimism thus also shapes which configurations appear most relevant.

Before parameterization, we had to decide on the scope of configurations to be included, for which we prioritized a comprehensive approach with four configurations at the expense of higher model complexity and parameterization effort. Fig. 5a shows PyCCS deployment when either only individual configurations or all four are available under the lower-cost parameterization. Deployment differs strongly, as only the heat-only configuration achieves levels comparable to those of full set of configurations. This demonstrates that including multiple configurations influences modeled deployment and the inferred PyCCS potential.

Table 5
Biochar parameterization variation for established configurations. See Table S2 for values.

	Baseline	Lower cost	Lower cost + higher efficiency
CAPEX	High capital cost (no learning)	From high to low capital cost, 10% learning rate per doubling of capacity	
Biochar application value	Lower material value	Higher material value	
Energy co-product efficiencies	Lower energy efficiencies		Higher energy efficiencies
Fraction of persistent carbon in biochar	80%		90%

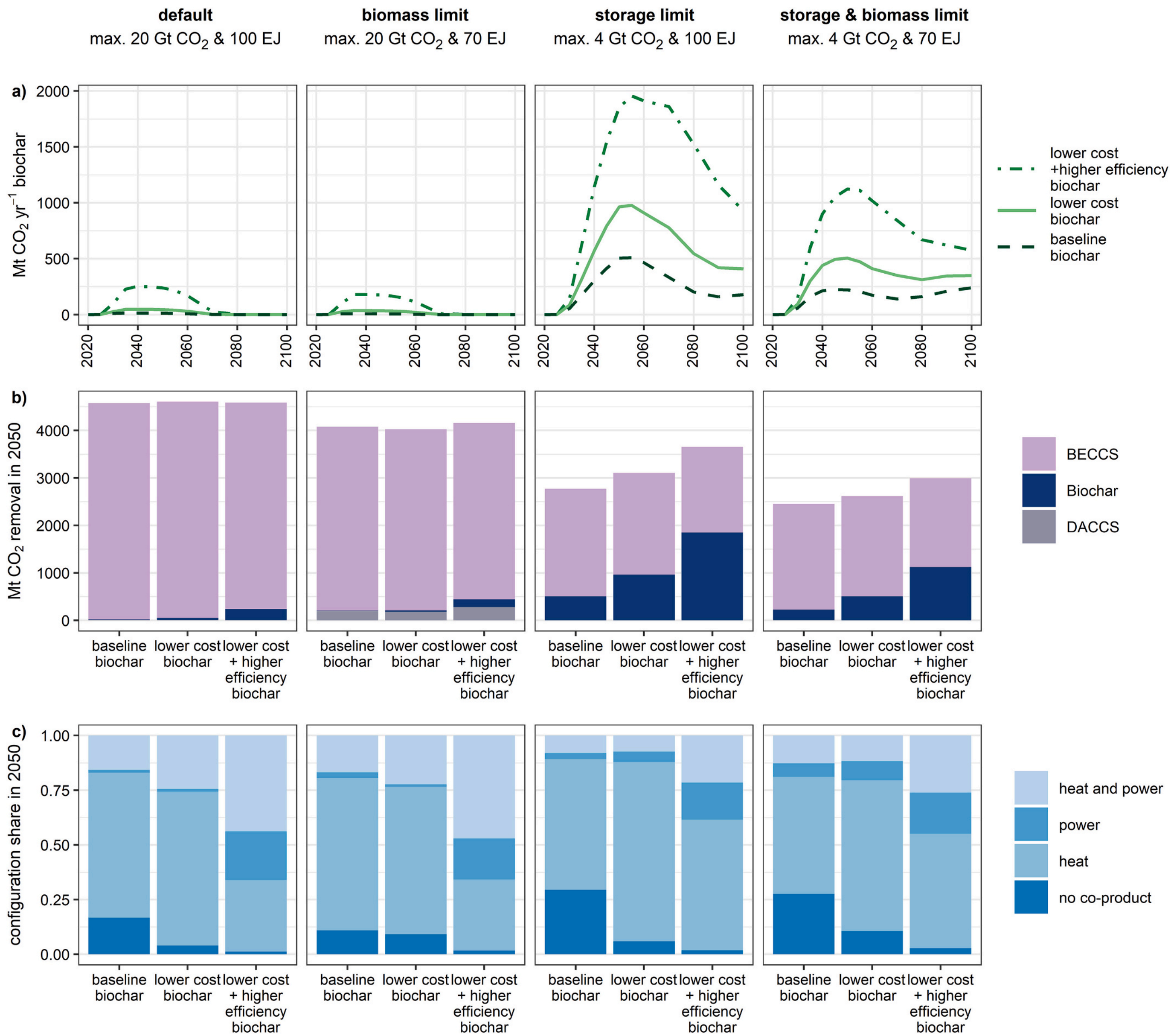

Fig. 4. Cost-effective CDR deployment and biochar production composition depending on scenario background conditions and optimism in the biochar parameterization for established biochar production configurations. The background condition description applies to each column. Panels a-c provide results for the three parameterizations for each background condition. Panel a) shows global PyCCS from 2020 to 2100, panel b) shows global novel CDR deployment including BECCS and DACCS, and panel c) the composition of the biochar configurations in 2050.

5.3. *Consequences of stylized biochar application representation*

Independent of the background and parameterization assumptions, global PyCCS peaks around the middle of the century, when the world reaches net zero CO_2 emissions (Fig. 4a). The decline in deployment after 2050 is partially related to the scenario design, which does not include a global net-negative emission target for the end of the century. Additionally, this pattern reflects the modeling of the material value of biochar application, which is held constant after 2050 (see Section 4.3). When production declines but applications have limited substitutes, sustained demand may increase the material value of biochar and dampen the reduction. Conversely, the current assumption may overestimate its material value at large-scale deployment. To assess this possibility, we conduct robustness experiments assuming zero material value from using the biochar, i.e., no co-benefits from biochar application to soils, in construction, or elsewhere. PyCCS decreases by 0.25 to almost 0.5 Gt CO_2 yr^{-1} in the *storage limit* scenarios (Figs. S6 and S7).

Despite this reduction, the maintained deployment indicates that PyCCS is primarily driven by high carbon prices reflecting high decarbonization pressure. This relates to results from the IAM GCAM, in which cropland application benefits are modeled explicitly, suggesting that carbon pricing drives biochar deployment and the realization of its co-benefits in agricultural application [10]. Nonetheless, the size of the effect in our stylized implementation is notable. Which application value *should* be assumed, i.e., how the consequences of overestimating or underestimating the application value are assessed, should be closely aligned with the overall scenario narratives.

5.4. *The effect of anticipating a more uncertain, advanced configuration*

Fig. 5b and c present exploratory results for adding an advanced bioliquid-producing route to the low-cost established configurations. Peak PyCCS is about 25% higher than when only established configurations with optimistic costs are included under geologic storage

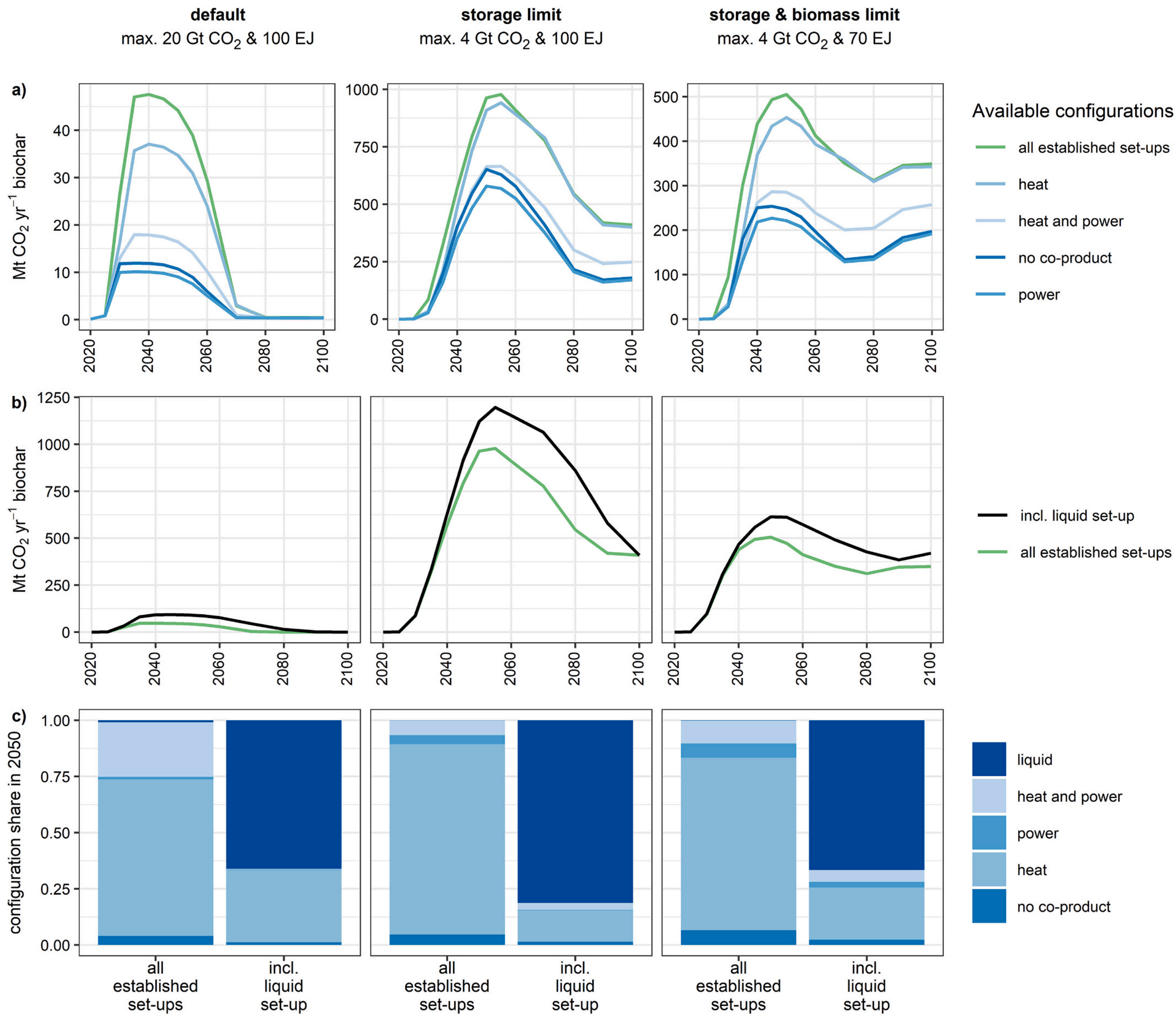

Fig. 5. Cost-effective biochar deployment and biochar configuration composition depending on the scope of configurations for different scenario background conditions, relating to comprehensiveness and confidence in advanced configurations. All scenarios apply the parameterization with lower cost for the established configurations. Panel a) shows global PyCCS from 2020 to 2100 for different modeled established set-ups. Panel b) shows the effect of adding a bioliquid-producing route to the established configurations. Panel c) details the composition of biochar configurations in 2050 for the scenarios in b).

limitations (Fig. 5b). The bioliquid set-up contributes the largest share in Fig. 5c, thus also replacing some established biochar production. This scenario result underscores that evaluating model optimism requires not only considering whether CDR technologies are included, but also which specific configurations are represented.

6. Discussion

6.1. Identifying value judgments in PyCCS representation

Value judgments affect the representation of technologies in IAMs because modeling requires numerous choices under uncertainty. This paper introduces a framework to identify such judgments in conjunction with techno-economic considerations, focusing on two entry points: configuration selection and parameter choice. For each step, what *could* be modeled depends on available evidence and narratives, what *can* be modeled is constrained by the model framework, and what modelers think *should* be modeled reflects epistemic and ethical considerations.

For the representation of biochar in IAMs, the analysis identifies important value-laden modeling choices. Biochar production encompasses many configurations with widely varying characteristics. Modelers must balance completeness with simplicity in their technology representation. The scenario analysis shows that an emphasis on completeness through broader coverage of biochar production configurations can increase modeled deployment.

For industrial configurations, dealing with uncertainty plays a central role. Advanced systems offer higher removal efficiency and more valuable co-products, making them relevant for the long-term horizon of models, but currently lack deployment. For a balanced CDR portfolio representation, their inclusion also depends on the uncertainty accepted for other technologies, particularly BECCS. Scenario results show that modeling an advanced bioliquid configuration can increase scenario deployment more than optimistic cost assumptions for established configurations. For parameterization, the collected data show a wide range of possible cost and efficiency assumptions. While not unique to biochar [85], differences in parameter choices across models deserve attention as biochar is increasingly implemented in IAMs. Finally, the representation of the material value from its application in different sectors also affects scenario deployment.

Further considerations relate to socio-political and carbon equivalence between PyCCS and other mitigation options [41]. For artisanal biochar production, integration into global carbon pricing schemes would raise international distributional concerns. Furthermore, the persistence of biochar carbon is context-dependent and remains subject to research [86]. It requires a judgment of the conditions under which PyCCS removals are considered sufficiently equivalent to avoided emissions [87]. The fraction of biochar carbon assumed to be permanent significantly affects scenario deployment.

6.2. Limitations and future work

The focus on the selection and parameterization of individual configurations does not capture the role of structural and scenario assumptions. In the scenario analysis, we thus include variation in bioenergy and geologic CO_2 storage assumptions. For low-overshoot 1.5 °C scenarios, we find that PyCCS reaches gigaton-scale deployment by mid-century only when geologic storage is more constrained than typically assumed in IAMs, for example due to institutional limitations [84].

While our analysis emphasizes the existing model context to ensure consistency and avoid bias against individual technologies, it does not address the techno-optimism embedded in the overall CDR portfolio. The identification of consistent variations in optimism across CDR approaches, including both configuration availability and parameter values, and their treatment across IAMs, is a subject for further research.

Another structural consideration concerns the incentivization of CDR. Our analysis assumes equal pricing of emissions and removals, reflecting the cost-effectiveness principle in IAMs. This embeds market-based distribution principles in the scenarios [23] and drives the dominant deployment of BECCS over biochar by prioritizing energy and removal efficiencies. In addition, the equivalent pricing of fossil and biogenic carbon can be questioned [41]. Future research should thus investigate scenarios with limited fungibility between different emissions and CDR approaches [88].

Finally, the modeling choices are influenced by the authors' positionality. As researchers based in Germany, our data sources, interpretation of uncertainties, and focus on industrial configurations are shaped by our European perspective.

There are also several techno-economic limitations in the biochar modeling. Our implementation focuses on biochar production set-ups, but interactions between different feedstocks, production systems, and applications call for further detail. For example, feedstocks are modeled in REMIND through aggregated supply curves with limited differentiation between feedstock types, yet feedstock characteristics affect conversion and removal efficiencies. Also, the implementation does not capture advantages of decentralized biochar systems.

On the energy system side, heat co-production is most valuable in the scenarios. However, REMIND's partially top-down approach to heat demand modeling might overestimate heat demand. Conversely, its limited representation of power system variability possibly underestimates the value of power co-production [72]. Future work should examine energy co-production in higher-resolution models, and explore bioliquid co-production in more detail.

To summarize, this paper provides a technology-focused approach to highlight value-laden assumptions, defend and discuss them in addition to robustness analyses of parameter assumptions, following the idea of deeper transparency in Bistline et al. [30]. Although such extensive documentation can be overwhelming for both modelers and users [89], it shows the relevance of making judgments about technology representation a subject of model comparisons and the exploration of emerging technologies in IAMs.

CRediT authorship contribution statement

Tabea Dorndorf: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nikolas Hagemann:** Writing – review & editing, Data curation. **Anne Merfort:** Writing – review & editing, Writing – original draft, Software. **Sabine Fuss:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Jessica Strefler:** Writing – review & editing, Writing – original draft, Supervision, Software, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: NH has contributed to the standards developed by Carbon Standards International including the European Biochar Certificate and Global Biochar C-Sink. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the German Federal Ministry of Education and Research through the projects CDRSynTra and CDRSynTra2 (TD, JS and SF, grant numbers 01LS2101G and 01LS2501G) and contributes to the project PyMiCCS (NH, grant numbers 01LS2109A and 01LS2109C). It was also supported by the European Union's Horizon 2020 - Research and Innovation Framework Programme through the project UPTAKE (AM, JS and SF, grant number 101081521).

The authors further gratefully acknowledge the European Regional Development Fund (ERDF), the German Federal Ministry of Education and Research and the Land Brandenburg for supporting this project by providing resources on the high-performance computer system at the Potsdam Institute for Climate Impact Research.

The authors thank the three anonymous reviewers for their constructive feedback, which significantly improved the clarity of this manuscript.

Appendix A. Supplementary information

Supplementary information to this article can be found online at https://doi.org/10.1016/j.erss.2026.104882.

Data availability

The biochar production data collection, REMIND scenario data, and plotting scripts are provided under a CC-BY-4.0 license on Zenodo (https://zenodo.org/records/15714397)

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