

Opposing Carbon Dioxide Removals and emissions reductions confuses mitigation policies

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Abstract

We analyse the relevance of Carbon Dioxide Removals (CDR) and emissions reductions (ER) categories for climate change mitigation, and assess associated methodologies used by carbon market crediting standards. We find that such a dichotomy is counter-productive for three reasons: (i) the economic dimensions to qualify CDR (intentionality, additionality, scope of projects) are overlooked in keystone definitions, which weakens the case for net zero objectives, (ii) methodologies by crediting standards are inconsistent and reveal the challenges for a practical distinction between CDR and ER, (iii) the distant prospects for net zero objectives and the vagueness of the concept of “residual emissions” challenge the relative urgency of acting on removals while large untapped potential remains for ER including via the development of new technologies. This assessment calls for at least two actions. At the very minimum, an improved definition of CDR with a better-defined scope, particularly for biomass-based activities, would guarantee its specific mitigation contributions compared to ER. More importantly we propose to move away from the CDR/ ER dichotomy, if only because mitigation actions tend to be hybrid, and to focus on the core characteristics that would lead to more efficient policies and funding allocation. Priority setting should thus be based on the following criteria in addition to the required additionality of any intervention: low costs of mitigation, no carbon leakage, high permanence, co-benefits, limited overall economic cost. Their application provides a more realistic and nuanced view on the content of the many mitigation actions and their contributions.

1. Introduction

Efforts to limit global warming are based on mitigation actions that limit concentrations of greenhouse gases (GHG) in the atmosphere. Originally such actions pertained to reducing emissions (or avoiding emissions – the difference is anecdotal for our analysis), for instance with changes in energy systems or in consumption patterns (Ivanova et al. 2020). This approach was promoted by the Kyoto Protocol in 1997 where the extent of emissions reductions (ER) from fossil fuels framed negotiations (McLaren and Markusson 2020). The Paris Agreement stated in 2015 that emissions must reach a global peak to hold warming well below 2°C (Rogelj et al. 2016). Yet the relatively slow pace of ER, shown for instance by country pledges covering only a third of the needs (UNEP 2017), has led to the realisation that more had to be done to avoid a climate catastrophe (IPCC 2022).

The idea to remove carbon from the atmosphere can be traced back to the influential work by Nordhaus (1992). Already in 2001, Obersteiner et al. highlighted the potential role of large-scale negative emissions for enabling ambitious climate mitigation targets that would otherwise be unattainable through conventional strategies. But attention towards carbon removals increased mostly when mitigation strategies shifted towards net zero objectives at country and corporate levels, as an implication of a focus on global carbon budgets and the acceptance of the overshoot paradigm, and made possible by promising technologies such as bioenergy with carbon capture and storage (McLaren and Markusson 2020). Indeed, carbon removals will be required to compensate emissions when only residual emissions

remain (Buylova et al. 2021). Reflections followed about the types of mitigation activities contributing to such Carbon Dioxide Removals (CDR) (Minx et al. 2017).

Yet, concerns about the deterrence effect of CDR for ambitious policies to reduce emissions in the near term were frequently expressed and taken seriously in mitigation circles (Carton et al. 2023). The relevance and risks of betting on CDR were discussed long ago (Fuss et al. 2014) while specific concerns about the incompatibility of most IPCC (Intergovernmental Panel on Climate Change) scenarios with sustainable development, when they involve CDR at scale, are well-identified (Deprez et al. 2024). Others point to the lack of consideration of knowledge previously generated by social sciences with carbon sequestration and sinks despite their relevance for more novel forms of CDR (Carton et al. 2020). But what might remain the most serious issue associated with the increasingly central role of CDR in the climate agenda is summarised in McLaren and Markusson (2020): *“the imagined technologies needed to meet [policies] in an ongoing cycle that repeatedly avoids transformative social and economic change”*.

The CDR definitions revolve around the principles of active removals of anthropogenic origin and durable storage. According to IPCC (2022): *“Anthropogenic activities removing carbon dioxide (CO₂) from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products”* (IPCC 2022). According to the ESABCC (2025), in line with Smith et al. (2024a): *“the activity must capture CO₂ [...] from the atmosphere (principle 1), durably store it with a characteristic storage duration of at least decades or more (principle 2), and must also be the result of a human intervention [...] (principle 3)”*.

Despite these converging definitions, there is a debate about the classification as CDR of certain mitigation actions such as CO₂ capture and storage at corn ethanol plants (Chay and Martin 2023) or biochar (Pirard 2024). This is critical for at least three reasons. First, the assessment of the respective contributions to net zero commitments and to the objectives included in the Paris Agreement must be robust, otherwise there is no guarantee that these objectives will be achieved. Second, basing decisions on unreliable definitions confuses the allocation of funds across mitigation actions; there is a risk of not paying for what is required as part of mitigation strategies. Third, with the cost of novel CDR being relatively high compared to ER, misleading definitions of CDR could lead to spending more for the same thing (ER) with less mitigation impact overall. Yet such cost spreads between the two main categories of mitigation involve economic stakes with expected resistance against reclassification, e.g. CDR-classified sectors gain from their status with a premium valuation on carbon markets.

While there has traditionally been an opposition between CDR and ER categories, its relevance is questioned in the context of offsetting for sub-global mitigation targets (Möllersten et al. 2024). Others have pointed to key additional principles that must underlie decisions on which mitigation actions to support, regardless of their classification and particularly the system in which they take place (Chay et al. 2025). Besides, we argue and propose to demonstrate that CDR is not only a mitigation action concept based on biophysical reasoning, or a technical one based on technology design, but also an economic one with consequences on how mitigation activities are classified.

In this analysis, we question whether the CDR/ ER classification system is relevant or even feasible for funding and policies. First, we assess its robustness and applicability by studying methodologies of crediting standards. Second, we test the robustness of CDR definitions and the risks of mistaking ER for CDR using biochar as a case study. Third, we discuss the validity of assumptions made to justify immediate investments in CDR and the higher costs of mitigation involved. Fourth, we analyse how, why and whether the classification of mitigation activities connects to different values (e.g. price of carbon credits).

2. The CDR concept is applied inconsistently across carbon crediting methodologies

At the national level, the distinction between CDR and ER is irrelevant for carbon accounting as all sources and removals must be included and aggregated to the extent possible. Indeed, when fluxes are considered, it does not matter whether fewer emissions take place or more carbon was sequestered, whether there is intentionality and permanent storage, as long as they take place in “managed land” according to IPCC definitions (as opposed to “unmanaged land”, e.g. rocky outcrops and sand deserts). A given country can operate at whatever level if net emissions are aligned with its commitments, which includes maintaining the “passive carbon uptake” (Johnstone et al. 2025) even though it enables countries to claim sequestration due to purely natural processes rather than policy (Allen et al. 2024).

But the classification of mitigation actions impacts the market valuation of carbon credits due to companies and individuals having their own legally binding targets and/ or voluntary objectives. For right or wrong, and supported by recommendations by the Science-Based Target initiative (SBTi), CDR credits are perceived as the most appropriate means to compensate for one’s emissions. This is despite the fact that net zero objectives can be achieved at sub-global level (e.g. company) equally with CDR or ER (Möllersten et al. 2024). This has led credit buyers – which represent a major source of mitigation funding – to make decisions based on the classification of credits along this line.

The system relies on the trading of credits either between countries (Internationally Transferred Mitigation Outcomes [ITMO]) or between entities towards voluntary mitigation targets (voluntary markets). It is thus critical to assess how crediting standards classify mitigation actions through an examination of their methodologies, and particularly whether CDR-classified credits meet the two basic requirements according to keystone definitions: active (anthropogenic) removal of carbon from the atmosphere and permanent storage.

To do so, we collected methodologies for carbon crediting and assessed their alignment with existing CDR definitions. We included VERRA as a leading standard, but also Puro.earth, Isometric and the portfolio of activities documented in The State of Carbon Dioxide Removal report (Smith et al. 2024a) to cover the entire spectrum. Indeed, the latter report includes additional activities such as ocean fertilisation, Bioenergy with Carbon Capture and Storage (BECCS), and ocean alkalinity enhancement.

Table 1 in the Supplementary Material contains the results. Here we provide the main findings:

- While several methodologies are hybrid and address both CDR and ER explicitly (VM0032, VM0033, VM0042) in their carbon accounting principles, they fail to state clearly which estimations lead to each category, hereby implicitly acknowledging that the frontier is blurred. Other methodologies are labelled as CDR but may include ER as well (e.g. Ocean Alkalinity Enhancement by Isometric, where reduced outgassing from the ocean is mixed with increased intake by the oceans);
- Definitions for CDR are applied inconsistently across methodologies, even within the same crediting standard. For example, the VM0042 on Agricultural Land Management suggests that using rather than burning residues leads to ER, whereas VM0044 on biochar classifies the processing of residues as CDR;
- In line with the IPCC (2022) and Smith et al. (2024a), methodologies consider that carbon capture due to anthropogenic activities counts as CDR regardless of project boundaries, while carbon capture from fossil sources counts as ER;
- Long-term storage of carbon tends to prevail over active removal to determine eligibility as CDR. This is illustrated, e.g. by the BECCS methodology that emphasises the storage in geological reservoirs while accepting any “sustainably sourced biomass”, which includes business-as-usual supplies when the facility is retrofitted. This aligns with the VCS program Definitions (v4.5) that include “*transfers of biogenic carbon from short-term to long-term carbon pools*” and the IPCC (2022) and Smith et al. (2024a) that exclude Carbon Capture and Utilization (CCU) when products do not guarantee long term storage (e.g. drinks or fuels).
- The key condition with long-term storage is also, and surprisingly, reflected in methodologies for ER. VM0018 targets the handling of solid waste in landfills and includes cardboard recycling, organic composting and aerobic decomposition, assuming that without permanent storage these activities cannot be classified as CDR; the notion of active removal is left aside.

Our assessment of methodologies suggests that neither intentionality (was the carbon captured within the scope of the intervention?) nor additionality (would the carbon have been captured without the carbon-related incentives?) is considered at the capture stage for CDR. Instead, only one of these conditions suffices: (i) carbon is biogenic, (ii) capture is of anthropogenic origin.

3. Case study of biochar: A hybrid mitigation action challenging the CDR/ ER dichotomy

Biochar is increasingly praised both for its potential as CDR (Lefebvre et al. 2023) and its variety of uses and co-benefits (Schmidt and Wilson 2014). It is produced out of organic material with a pyrolysis process and can store carbon for very long periods, up to a thousand years. As described in Wu et al. (2019), this product has been identified for its mitigation potential since at least 1998, and the establishment of the International Biochar Initiative (IBI) in 2006 has been instrumental in making it consensual in climate discussions.

In the related forums and literature (e.g. Lehmann et al. 2021), including the reports by the IPCC (2022), biochar is presented as a CDR. This is translated in the price of carbon credits up to USD 200/tCO₂-eq (<https://puro.earth>), more than ten times above average emissions reductions' values. According to Smith et al. (2024b), 14% of deals on CDR technologies since 2020 are about biochar; when combined with DACCS, they are the CDR types receiving the most funding, with \$808 million to DACCS in 2022 and \$234 million to biochar in 2023. In terms of actual removals, biochar is the leading novel CDR.

The classification of biochar deserves scrutiny; it also illustrates the need to move beyond a purely biophysical approach to an economic one. We argue that according to the economic approach, the action of removing carbon from the atmosphere must be attributed to the intervention to qualify as CDR, i.e. it must be within its boundaries/ scope (Fig. 1) for which the additionality is assessed. The concept of additionality encapsulates this link between the type of feedstock and the classification of biochar to ensure that carbon removals from the atmosphere would not take place without the incentives created by the opportunity for carbon revenue, i.e. they are not business-as-usual.

Feedstock options differ mainly in one dimension that matters here: were they cultivated for the purpose of biochar production, or for any other reason? If we focus on the main feedstocks available with limited risks for food security and biodiversity, namely agricultural residues, forestry residues, animal manure, wastewater biosolids and waste biomass resulting from land restoration (Lefebvre et al. 2023), it is straightforward that the biomass is not purpose-grown. In contrast, in other cases that remain poorly documented such as dedicated woodlots and sustainable forestry management, biomass production and associated removals should be attributed to biochar.

Figure 1 summarises the interactions between the types of feedstocks and additionality; it shows that biochar should only be considered a CDR in very specific, and rarely seen, situations. These situations are displayed in the left column. Yet, what happens most of the time is that agriculture and forestry residues are used as feedstock (Table 1) and biochar production only changes the ultimate form and thereby prevents the release of GHG gases (right column of Fig. 1), thus preventing emissions by ensuring long term storage.

Table 1
Status of biochar as CDR or ER for the main feedstock options

Feedstock option	Status of biochar from a climate change mitigation perspective	Likelihood
Agricultural residues: e.g. corn stover, rice straw, sugarcane bagasse, wheat straw, cotton stalk	ER compared to a situation where residues are burnt or left to decay	Very common
Forestry residues: e.g. tree branches and twigs, bark, sawdust	ER compared to a situation where residues are burnt or left to decay	Common
Dedicated tree plantations/ crop farming (exclusively established for biochar production)	CDR	Uncommon
Land restoration with clear cutting of invasive trees	ER compared to a situation where woody biomass is burnt or left to decay	Uncommon
Dedicated sustainable management of areas invaded by trees with application of a rotation system in woodlots	CDR	Uncommon
Sustainable natural forest management with enhanced carbon removals after harvesting	CDR	Uncommon
Note: we do not address cases where feedstock would have been used for bioenergy in the absence of biochar production; it should be assessed on a case-by-case basis, e.g. because it could lead to fossil fuel substitution.		

It is important to understand the reasons leading to what we consider to be an erroneous classification of biochar as CDR. Apart from vested interests with biochar stakeholders enjoying higher revenues with premium carbon credits (section 5), especially in a context where the business case for biochar remains fragile, we believe that a certain inertia in the scientific and policy forums plays a role. Based on our analysis of general (IPCC) and practical (methodologies for carbon crediting) definitions, we found that permanent storage prevails over the active removal for classification as CDR; furthermore, a special status is provided to biogenic carbon. This is also reflected in Swoboda and Oschlies (2025), who consider that reducing carbon emissions from labile to long-lasting pools should be eligible as CDR. They make a move in the right direction when considering that carbon feedstock sequestered long ago does not pass the test of additionality because it cannot be expected to be released any time soon. But they fall short of including the intentionality of carbon sequestration within the scope of the intervention.

In fact, biochar is a hybrid mitigation action: while not actively removing carbon from the atmosphere in the vast majority of cases, it removes it from the natural cycle; while potentially avoiding emissions for a long time (possibly so for thousands of years), its permanence depends on the production process and use, and co-benefits (including boosting sequestration due to higher plant productivity) remain disputed and context-dependent.. For these reasons, we argue that biochar holds potential to perform well on the permanence of the mitigation effort as well as its co-benefits. As such, it should be seen as a complementary option alongside the myriad activities for ER, but not as a CDR by default.

4. The case for CDR relies on debatable assumptions about the possibility to achieve net zero

The main advantage with CDR is the compensation for residual emissions, i.e. those that are hard to abate once emissions caused by human activities or natural processes have been curbed to the maximum from a social-economic-technical perspective. This concept lacks a consistent application as reflected in the mitigation strategies submitted by countries (Buck et al. 2023) and can be quantified under the assumptions of a specific model and mitigation scenario that determine which ER are feasible (Luderer et al. 2018). Therefore, all depends on the assumptions – which are debatable by principle – determining which abatement remains economically or socially unacceptable, or technically infeasible. For instance, different levels of carbon tax would result in different levels of residual emissions due to the variability in the economic feasibility of emitting activities and technologies. The IPCC (2018) provides a definition by default of residual emissions, stating that these are emissions that must be balanced to achieve climate neutrality. Consequently, CDR and residual emissions are tied conceptually to net zero objectives. All in all, it appears that the concept of residual emissions is relative and can be instrumentalised for any given objective.

The reasoning about CDR, net zero and residual emissions must be put in the perspective of mitigation achievements so far. An examination of submitted long-term low-emissions development strategies (LT-LEDS) indicates that residual emissions for Annex I countries represent 17.9% of their current emissions, hence about 80% of their emissions must be curbed before reaching the residual emissions stage (Buck et al. 2023). Another study finds average residual emissions for Annex I countries at 25%, and much higher for non-Annex I countries at 41%, but also points to the fact that only a minority of scenarios provide a quantification (Smith et al. 2024b). It is reasonable to assume that such levels of abatement will not be achieved in the near and mid-term, so that reducing emissions should be a priority for mitigation, not high-cost CDR with few or no co-benefits. Furthermore, Smith et al. (2024b) notice that some countries plan for high levels of expected residual emissions due to the retention or expansion of fossil fuel production and use, using more CDR to achieve net zero rather than pushing their residual emissions down.

In this context, the premium on CDR carbon credits (see next section) must be questioned. In practice, carbon credit market valuations are not only related to actual costs but also to statements, policies and standards' recommendations that support CDR over ER. While this can lead to sound premiums, such as for co-benefits, we point to their misleading effects in the case of CDR. Indeed, the higher market valuation is interpreted as a sign of virtue regardless of the consequences for the optimal allocation of mitigation funding. This situation is derived from the assumption that removals must be supported early on, regardless of the effectiveness of policies to reduce emissions. In a context of largely untapped potential for ER we argue that this is a debatable assumption with significant consequences on mitigation outcomes.

5. The CDR/ ER classification system impacts the market valuation of mitigation actions

Due to the role of carbon markets in mitigation funding, the valuation of credits has an impact on the quantity and quality of mitigation. Carbon credits are not a commodity; they sell at different prices depending on their characteristics (Forest Trends' Ecosystem Marketplace 2025), including their social and environmental impacts. Besides, the lower the value of a high-integrity carbon credit, the greater the volume of mitigation achieved for a given level of funding because more carbon credits can be bought (and projects funded). Lower value credits orient investments towards the low-hanging fruit mitigation activities, which admittedly may also perform poorly on other social and environmental dimensions.

In other words, the characteristics of carbon projects go beyond mitigation impacts (e.g. permanence of sequestration) and include co-benefits or risks. Typically, nature-based solutions (NbS) such as avoided deforestation or sustainable agriculture have relatively high valuations due to their alleged ability to enhance livelihoods and biodiversity preservation (Forest Trends' Ecosystem Marketplace 2025). While carbon markets have initially been conceived as a place to exchange a commodity based on the tCO₂-eq metric, in reality, they are complex and multidimensional.

Smith et al. (2024a) provide data on market valuation for the years 2022 and 2023 aggregated from the six major registries and platforms: Verra, Gold Standard, the American Carbon Registry, CDR.fyi, Puro.earth and Climate Action Reserve. A first key finding is the divide between novel (e.g. DACCS, BECCS, biochar) and conventional (mostly NbS) CDR technologies. The former projects attract rapidly increasing investments (yet starting from a low point) with credit values orders of magnitude higher than conventional CDR, which in turn is valued significantly more than other activities. For the sake of illustration, the weighted average price of carbon credits in 2023 for direct ocean capture and storage and afforestation/ reforestation is respectively USD 1,402 and USD 16, while those for ER hardly exceed USD 5.

Another finding is that novel technologies for CDR rely on voluntary markets for their funding, which requires large premiums paid by private companies. This has started to materialise with significant investments by major technology companies (Newsweek 2024). A recent survey by CDR.fyi (2024) also showed that credit buyers aim to be associated with spectacular breakthroughs. Despite the visibility of novel CDR in the media and literature on mitigation as well as efforts to integrate them in the emerging regime under Article 6 of the Paris Agreement, they are scarce in public policies (counter examples of state contributions exist, e.g. Ahonen et al. 2025).

The specific status of CDR (especially novel) in the carbon credit market valuations may be justified by their experimental component and high costs before they would become affordable once mature. As such, their funding requires investors to accept paying more for a similar mitigation impact, or at least for the same amount of carbon credits. This in turn may be more palatable with a registry system that gives more visibility to such specific types of carbon credits and investments because investors are

interested in having their contribution acknowledged publicly. Yet, this also poses a broader question about the lack of high carbon market valuations for experimental and innovative ER activities that would lower the volumes of residual emissions, and in turn the need for CDR. Innovation is required to combat climate change, and should be supported, but it does not have to be associated exclusively with CDR.

6. Conclusions

While CDR has gained popularity in the portfolio of mitigation strategies, we demonstrate that the concept is flawed and its application leads to inconsistencies as illustrated by various standard methodologies used in carbon markets. The analysis of biochar, which represents a range of biomass-based CDR activities for which the same lessons apply, demonstrated a confusion with ER. Indeed, the introduction of the economic dimension to assess the eligibility shows that it should only qualify as CDR if it combines the two necessary conditions of actively removing carbon from the atmosphere and storing it permanently. Yet the main and institutional definitions of CDR, as well as practice, fail to impose the first condition and create opportunities to mistake ER for CDR. This is further reflected in the analysis by Swoboda and Oschlies (2025): while useful in pointing to the variety of CDR activities, they perpetuate the confusion around the specificity of CDR, namely that carbon capture from the atmosphere should be active and additional in the first place.

We propose to extend the assessment to the realm of mitigation actions, including ER, by arguing that there is a continuum of situations rather than a dichotomy because each and any mitigation action is a combination of many parameters (e.g. permanence, leakage, additionality, co-benefits, costs-effectiveness, reliability). Yet the strong interest in CDR is fuelled exclusively by net zero commitments and the realisation that emissions will have to be compensated globally, both contemporaneously (residual emissions) and inter-temporally (overshoot compensation) to achieve the goals of the Paris Agreement. In fact, this is only relevant at the stage of residual emissions, which remains a distant prospect. The realisation that global warming could not be contained under 1.5°C in a context of ever-increasing emissions (Forster et al. 2025) is evidence that significant untapped potential remains for ER and should be addressed immediately. The minimisation of residual emissions by acting first and foremost on ER should be the mitigation priority, among others to avoid a carbon lock-in (Luderer et al. 2018). Yet the higher valuation of CDR on the carbon markets, which suggests greater merits compared to ER, implies a lower mitigation impact at similar levels of investment; it also acts as a distraction from system changes.

As the world lags behind its mitigation objectives, and considering the various issues and inconsistencies associated with the use of CDR (including the uncertainties around the real potential for geological storage that remains disputed, Gidden et al. 2025), we recommend focusing on the basic and widely agreed characteristics of mitigation actions to orient policies and channel funding. This is all the more necessary since mitigation actions tend to possess various combinations of characteristics of relevance for sustainable climate change mitigation; they are usually hybrid activities rather than distributed across the CDR/ ER dichotomy. For these reasons, we suggest the following five criteria to

set priorities: low costs of implementation, limited economic impacts (e.g. in terms of opportunity costs or reduced productivity), high degree of permanence, absence of carbon leakage, co-benefits/ no adverse impacts.

The justification for the popularity of CDR while the stage of residual emissions is not within reach, remains unstated. We suggest several reasons: the faith in new technologies, the lack of political or societal will for drastic ER based on system change, the business opportunities associated with such innovations. CDR can be one element of the solution also on the shorter term but only if eligible actions perform well on these criteria; it should not receive premiums because of an alleged yet debatable superiority over ER. This diagnosis might change when and if the stage of residual emissions becomes within reach.

Declarations

The authors report there are no competing interests to declare.

Author Contribution

R.P. designed the research, analysed the data and wrote the main manuscript text. K.M. reviewed the manuscript and revised it.

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References

1. Ahonen H-M, Dufour M, Honegger M, Michaelowa A, Möllersten K, Poralla M, Samaniego X, Veen P, Weldner K (2025) Promoting biogenic carbon capture and storage in the Nordic region through carbon markets, Discussion Paper, Perspectives Climate Research & KTH Royal Institute of Technology
2. Allen MR et al (2024) Geological net zero and the need for disaggregated accounting for carbon sinks. *Nature* 638:343–352
3. Buck HJ, Carton W, Lund JF, Markusson N (2023) Why residual emissions matter right now. *Nat Clim Change* 13:351–358

4. Buylova A, Fridahl M, Nasiritousi N, Reischl G (2021) Cancel (out) emissions? The envisaged role of carbon dioxide removal Technologies in Long-Term National Climate Strategies. *Front Clim* 3(July):1–16
5. Carton W, Hougaard I-M, Markusson N, Lund JF (2023) Is carbon removal delaying emission reductions? *WIREs Clim Change* 14
6. Carton W, Asiyambi A, Beck S, Buck HJ, Lund JF (2020) Negative emissions and the long history of carbon removal. *WIREs Clim Change* 11
7. CDR.fyi, 2024, *Market Outlook Summary Report*. <https://www.cdr.fyi/blog/2024-market-outlook-summary-report>
8. Chay F, Martin K (2023) Ethanol carbon capture and storage isn't carbon removal CarbonPlan <https://carbonplan.org/research/ethanol-cdr-claims>
9. Chay F et al (2025) 'What is CDR?' is the wrong question CarbonPlan <https://carbonplan.org/research/defining-good-cdr>
10. Deprez A, Leadley P, Dooley K, Williamson P, Cramer W, Gattuso J-P, Rankovic A, Carlson EL, Creutzig F (2024) Sustainability limits needed for CO₂ removal. *Science* 383(6682):484–486
11. ESABCC (2025) Scaling up carbon dioxide removals: Recommendations for navigating opportunities and risks in the EU. European Scientific Advisory Board on Climate Change, Denmark
12. Forest Trends' Ecosystem Marketplace (2025) State of the Voluntary Carbon Markets 2025: Meeting the moment, Renewing trust in carbon finance. Forest Trends Association, Washington DC
13. Forster PM et al (2025) Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence. *Earth Syst Sci Data* 17:2641–2680. <https://doi.org/10.5194/essd-17-2641-2025>
14. Fuss S, Canadell JG, Peters GP, Tavoni M, Andrew RM, Ciais P, Jackson RB, Jones CD, Kraxner F, Nakicenovic N, Le Quéré C, Raupach MR, Sharifi A, Smith P, Yamagata Y (2014) Betting on negative emissions. *Nat Clim Change* 4:850–853
15. Gidden MJ, Joshi S, Armitage JJ, Christ A-B, Boettcher M, Brutschin E, Köberle AC, Riahi K, Schellnhuber HJ, Schleussner C-F, Rogelj J (2025) A prudent planetary limit for geologic carbon storage. *Nature* 645:124–136
16. IPCC (2022) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, P.R. Shukla (Eds.), Cambridge University Press, Cambridge
17. Global Warming of 1.5°C, Masson-Delmotte P, Zhai H-O, Pörtner D, Roberts J, Skea P, Shukla A, Pirani W, Moufouma-Okia C, Péan R, Pidcock S, Connors JBR, Matthews Y, Chen X, Zhou MI, Gomis E, Lonnoy (2018) An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Cambridge University Press. T. Maycock, M. Tignor, & T. Waterfield (Eds.)]

18. Ivanova D, Barrett J, Wiedenhofer D, Macura B, Callaghan M, Creutzig F (2020) Quantifying the potential for climate change mitigation of consumption options. *Environ Res Lett* 15:093001. 10.1088/1748–9326/ab8589
19. Johnstone I, Allen M, Axelsson K, Caldecott B, Eyre N, Fankhauser S, Hale T, Hepburn C, Hickey C, Jenkins S, Khosla R, Lezak S, Smith A, Smith SM, Wagner A (2025) The revised oxford principles for net zero aligned carbon offsetting. *Environ Res Lett* 20:091005
20. Luderer G et al (2018) Residual fossil CO₂ emissions in 1.5–2°C pathways. *Nat Clim Change* 8:626–633
21. McLaren D, Markusson N (2020) The co-evolution of technological promises, modelling, policies and climate change targets. *Nat Clim Change* 10:392–397
22. Minx JC, Lamb WF, Callaghan MW, Bornmann L, Fuss S (2017) Fast growing research on negative emissions. *Environ Res Lett* 12(3):035007
23. Möllersten K, Dufour M, Randall Spalding- Fecher (2024) Demystifying carbon removals in the context of offsetting for sub-global net-zero targets. *Carbon Manag* 15(1):2390840. 10.1080/17583004.2024.2390840
24. Newsweek (2024) Why Big Tech is pumping big money into companies pulling CO₂ from the air, accessed July 8, 2025
25. Nordhaus WD (1992) An optimal transition path for controlling greenhouse gases. *Science* 258(5086):1315–1319
26. Obersteiner M, Azar C, Kauppi P, Möllersten K, Moreira J, Nilsson S, Read P, Riahi K, Schlamadinger B, Yamagata Y, Yan J (2001) Managing climate risk. *Science* 294(5543):786–787
27. Pirard R (2024) Is biochar a Carbon Dioxide Removal? *Bois et Forêts. des Tropiques* 361:1–8
28. Rogelj J, Höhne N, Fransen T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K, Meinshausen M (2016) Paris Agreement climate proposals need a boost to keep warming well below 2°C. *Nature* 534:631–639
29. SBTi (2024) SBTi corporate net-zero standard criteria (version 1.2 – March 2024), Science-Based Target initiative
30. Smith SM et al (eds) (2024a) *The State of Carbon Dioxide Removal 2024–2nd Edition*
31. Smith HB, Vaughan NE, Forster J (2024b) Residual emissions in long-term national climate strategies show limited climate ambition. *One Earth* 7:867–884
32. Swoboda S, Aschlies A (2025) Limits to CDR accounting: the role of carbon fluxes, time(liness) and storage. *Environ Res Lett* 20:071003. <https://doi.org/10.1088/1748-9326/adde73>
33. UNEP (2017) The Emissions Gap Report. United Nations Environment Programme, p 112

Figures

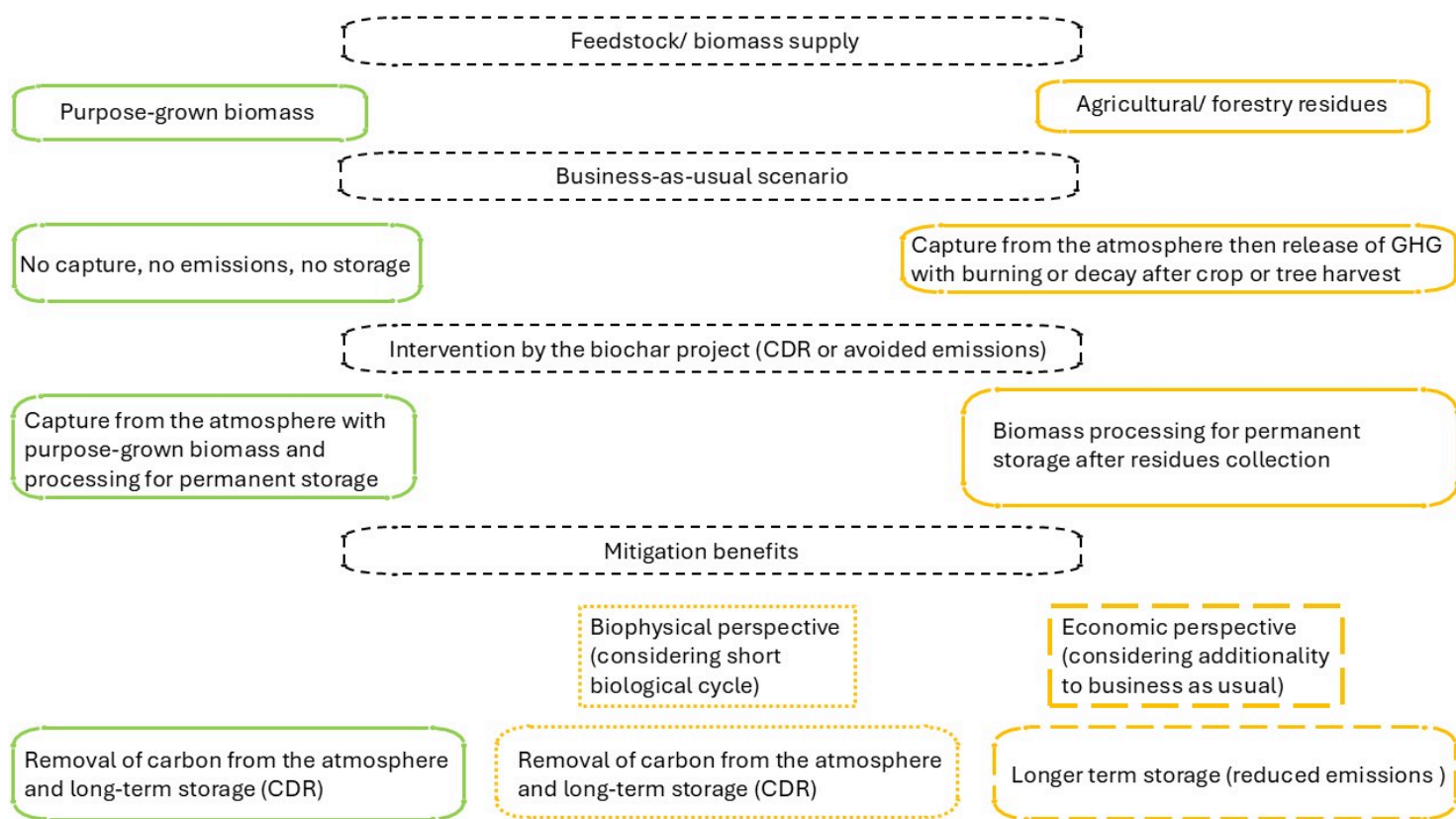


Figure 1

An economic approach to CDR clarifies its difference with ER: Case of biochar

Note: The figure describes all stages for a mitigation action that processes biomass into biochar. The stages encircled in green refer to a situation where the project should qualify as CDR. The stages encircled in orange refer to a situation where the classification of the mitigation action as CDR or ER depends on the angle, either from a biophysical perspective or an economic perspective – the difference lies with the scope and whether the capture stage is included in the project.

Supplementary Files

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- [SupplementaryMaterials.docx](#)