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Carbon markets for carbon dioxide removal

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ABSTRACT

Closing the carbon dioxide removal (CDR) gap requires significant capital deployment. Carbon markets – both compliance and voluntary forms – are a central tool to raise such investment. However, for them to do so efficiently requires understanding the current and future market dynamics: between CDR and other forms of emission reduction and avoidance projects, as well as between conventional and novel forms of CDR. This perspective article outlines current trends related to the role of CDR in the voluntary carbon market. It then builds on this by exploring future developmental pathways for CDR via the voluntary carbon market as well as emerging international and domestic compliance carbon market regimes. It shows that while the use of such market mechanisms to support CDR has thus far been comparatively limited, the fundamentals are there for them to be effective tools in scaling CDR in future. Further developments are however needed for them to be a successful diffuser of CDR in this regard.

Key policy insights

- CDR projects only make up a fraction of the current voluntary carbon market in comparison to emission reduction and avoidance projects.
- Even so, the voluntary carbon market has played a critical role in testing the viability of a wide range of CDR pathways, providing a particularly catalytic role for novel CDR.
- Integrating CDR into compliance carbon markets – both domestically and internationally – will be crucial to scaling CDR to the levels needed to achieve the goals of the Paris Agreement.
- For this to occur effectively, it is imperative that high quality CDR is appropriately distinguished from other forms of mitigation outcomes, and that harmonization between domestic and international policy settings is promoted.

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1. Introduction

Carbon markets can deliver a broad range of climate mitigation outcomes, including projects that avoid, reduce and remove greenhouse gases. Carbon markets have largely not focused on the deployment of carbon dioxide removal (CDR) to date, though this could shift in future. The successful negotiations at COP29 marked an important milestone for the establishment of a global quasi-compliance carbon market under the Paris Agreement Carbon Crediting Mechanism (PACM) under Article 6.4 as well as a broader option to trade mitigation outcomes through cooperative approaches under Article 6.2 (Johnstone, 2024). Such channels – in tandem with

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compliance markets – could enable significant CDR deployment in the long term. In the near term, leveraging complementary voluntary demand as well as the development of supplementary national funding mechanisms will be essential to sustain the scale-up of CDR efforts.

CDR describes human activities that capture CO_2 from the atmosphere and store it durably in geological, land or ocean reservoirs or in products (IPCC, 2022). CDR involves both conventional methods, such as afforestation/reforestation, which tend to be already deployed at scale as well as novel methods, which tend to have lower technological readiness levels and be operating on a much smaller scale, such as direct air carbon capture and storage (DACCS) (Smith et al., 2024). As a form of climate change mitigation CDR projects can produce carbon credits. Carbon credits represent 1t CO_2e avoided, reduced or removed and are produced according to an applicable carbon crediting methodology and validation process. The voluntary carbon market (VCM) is the primary platform where carbon credits are purchased. However, due to the increasing fungibility of carbon credits across systems, we are seeing a greater degree of interplay between the VCM, domestic carbon pricing mechanisms as well as the emerging international quasi-compliance architecture underpinned by Article 6 of the Paris Agreement. This evolution has implications for CDR deployment via carbon market mechanisms both now and in the future. In Section 2 this perspective provides an analysis of the new data provided by the State of CDR Report on the role of CDR in the VCM (Fuss et al., 2024). It then builds on this analysis to explore the role of CDR in future compliance markets in Section 3. Section 4 concludes with an outlook and some caveats for the transition from the VCM to compliance markets, also discussing the potential future role of the VCM for CDR in future. Understanding these dynamics is important given the significant financial flows required to deploy levels of CDR consistent with the Paris Agreement and the raft of potential policy options that exist to help plug this gap within this context, including those outlined by Edenhofer et al. (2023) and Kalkuhl et al. (2022).

2. State of play of CDR in carbon markets

CDR projects differ from emission reduction and avoidance projects: CDR activities reduce the concentration of atmospheric greenhouse gases by removing CO_2 , while avoidance and reduction activities lower future CO_2 emissions (Figure 1).

As CDR is still largely absent from most national decarbonization plans, the VCM can play a key role in financing CDR projects, particularly novel kinds. CDR credits are issued on the VCM via established registries such as Verra, Gold Standard, American Carbon Registry & Climate Action Reserve as well as through new novel CDR-focused registries such as Puro and Isometric. Purchasers buy already issued or future credits directly from suppliers or through intermediaries and buyers (CDR FYI, 2024a). Here we explore trends in CDR deployment via the VCM through reference to the trends outlined in the 2024 State of CDR Report (Fuss et al., 2024).

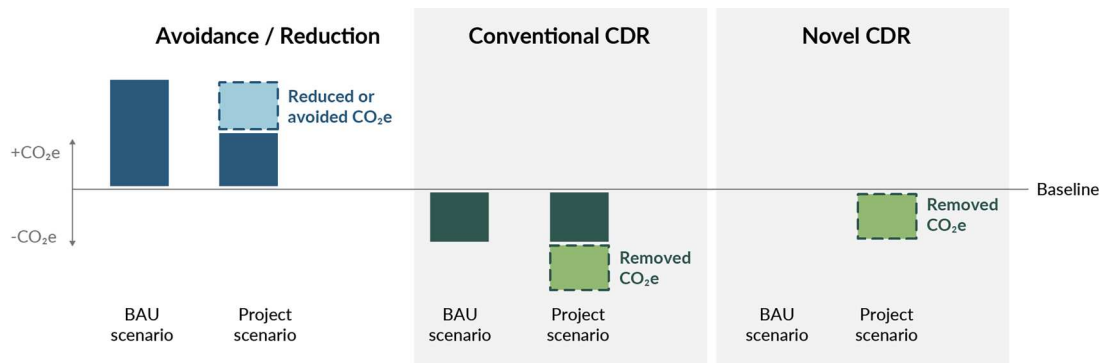


Figure 1. Avoided and reduction credits (in blue) represent the reduction of future emissions compared to the business-as – usual (BAU) scenario. The dashed area illustrates the project’s impact and the number of credits generated. CDR projects (in green) are assessed based on the additional amount of CO_2 removed from the atmosphere, compared to the BAU scenario. For novel CDR the BAU scenario is often assumed as zero, yet this may be subject to future amendments. Reproduced from Fuss et al. (2024) with the authors’ permission.

The vast majority of carbon credits retired on the VCM (where ‘retired’ means the environmental benefit is claimed by one distinct party and thus no longer tradable) relate to projects that avoid or reduce emissions. While these atmospheric impacts are distinct, a significant proportion of incumbent projects adopt a mixed methodology making it impossible to distinguish the exact volume of CDR credits some projects may generate. Even so, in 2023, CDR credits accounted for less than 10% of total credits sold on the VCM (Fuss et al., 2024) (Figure 2).

One reason why CDR credits make up a small proportion of the VCM is that the price for a CDR-based carbon credit is substantially higher than other credit types. On average, conventional CDR credits (which ranged from \$12 to \$16 in 2023) cost three times more than credits generated from emission reduction or avoidance projects (Fuss et al., 2024). The average weighted price for novel CDR credits (which ranged from \$111 to \$1,608 in 2023) exceeds the price for credits from emission reduction or avoidance projects by a factor of 100 (Fuss et al., 2024). While the higher price and lower technology readiness levels are undoubtedly detrimental to the demand for CDR credits compared to other types of carbon credits, credit supply and risk of reversal can also sway potential buyers.

Aside from price, there are noticeable differences between types of CDR on the VCM. The conventional CDR market is more mature and tends to be traded through established carbon crediting registries, whereas the novel CDR market tends to have a more nascent and bespoke market infrastructure (Fuss et al., 2024). Direct comparison of transactions of conventional and novel CDR is often difficult as conventional CDR credits tend to be sold ex-post after the project has occurred, while novel credits are typically sold ex-ante as pre-purchases. Using the common denominator ‘demand’, which encompasses both sold credits (for forward purchases) and retired credits (for issued credits) the number of credits sold for conventional CDR fell slightly in

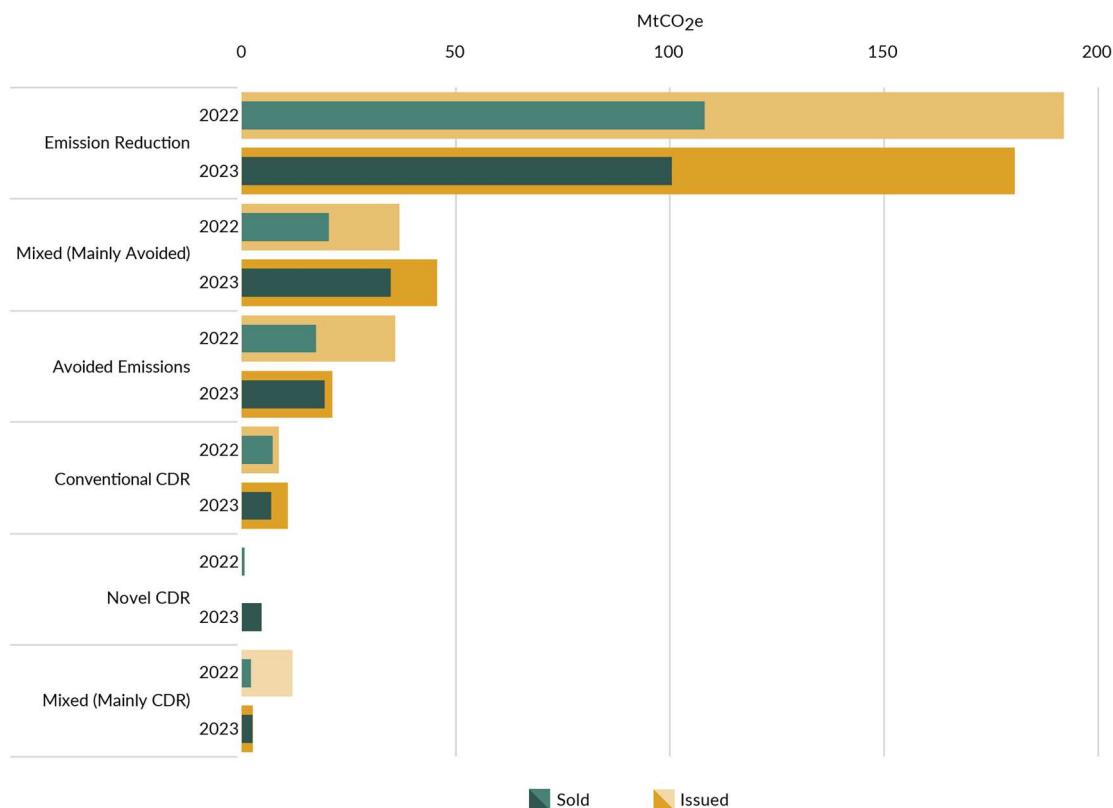


Figure 2. Volume of carbon credits issued and sold on the voluntary carbon market, by project methodology type, 2022–2023. CDR = carbon dioxide removal. Reproduced from Fuss et al. (2024) with authors’ permission.

2023 from approximately 9.36 million to 9.32 million, while purchases of future novel CDR credits grew seven-fold from 600,000–4.6 million (Fuss et al., 2024) (Figure 3).

This trend of rapid growth in novel CDR continued in 2025, with nearly 8 million tCO_{2e} purchased during the year (CDR FYI, 2025). Despite conventional CDR generating more credits than novel CDR, the VCM has played a far more catalytic role in financing novel CDR than conventional CDR. Credits issued for afforestation/reforestation represent less than 1% of the overall number of afforestation/reforestation activities CDR that occurred in 2023 (Fuss et al., 2024). By contrast, pre-purchases for novel CDR well exceeded the total amount removed

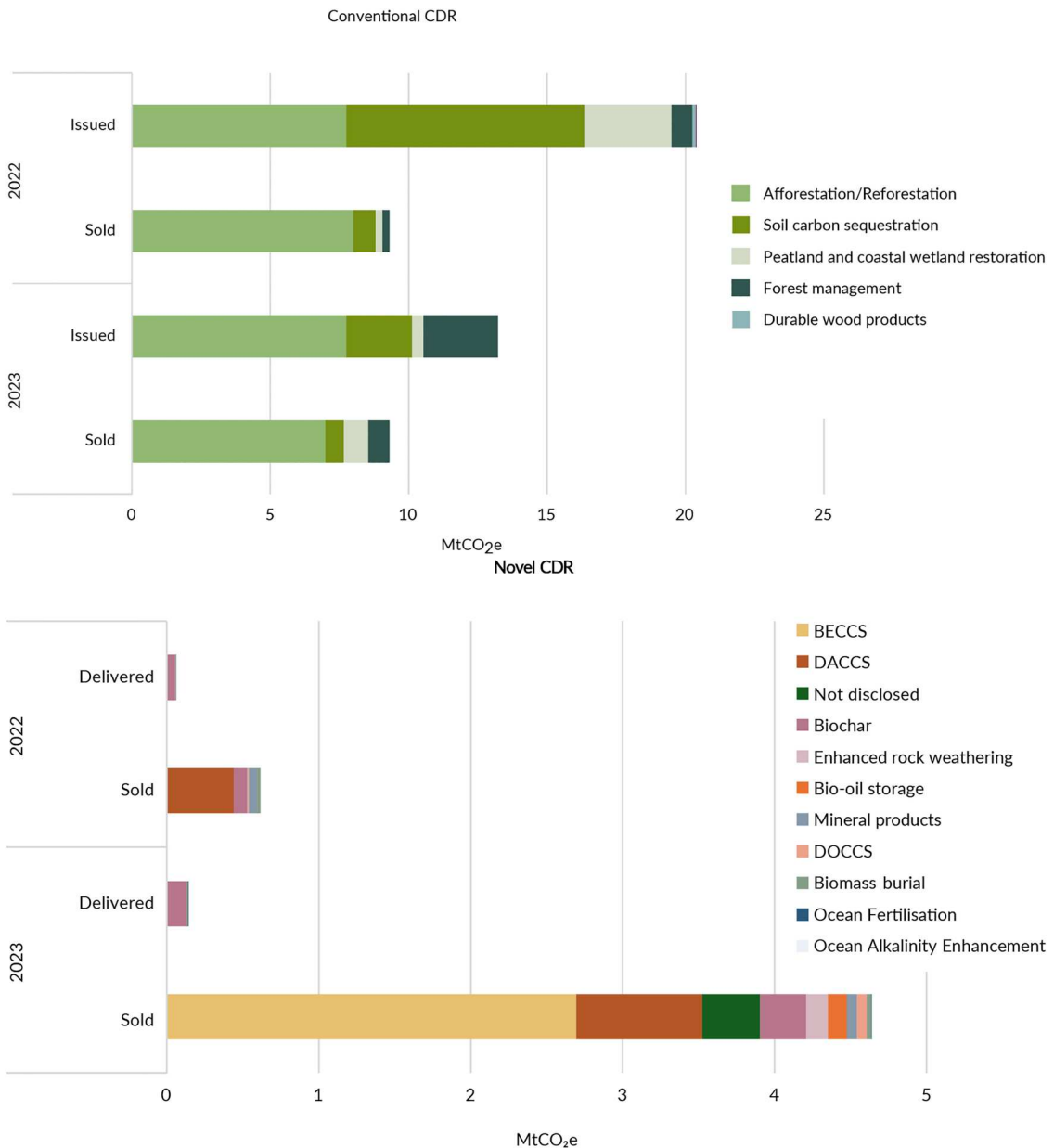


Figure 3. Breakdown of the volume of carbon dioxide removal (CDR) in the voluntary carbon market (VCM) by CDR method, 2022–2023. Top panel: conventional CDR; bottom panel: novel CDR. BECCS = bioenergy with carbon capture and storage; DACCS = direct air carbon capture and storage; DOCCS = direct ocean carbon capture and storage. Reproduced from Fuss et al. (2024) with authors’ permission.

through novel methods in 2023 (Fuss et al., 2024). These numbers demonstrate that novel CDR projects are heavily reliant on accessing finance through the VCM, without which they likely would not exist. Indeed, most novel CDR deployment in the market has been driven by few large offtake agreements from individual buyers, particularly Microsoft whose purchases represent over 70 percent of all novel carbon removal credits sold to date (CDR FYI, 2024).

In terms of geographical distribution, VCM projects which include some form of CDR activity are more prevalent in the northern hemisphere than in the southern hemisphere and are especially concentrated in North America, this distribution is largely due to the substantial presence of forest management projects in Mexico and the US (Fuss et al., 2024). 401 novel CDR suppliers are listed with a known headquarter location by CDR.fyi. Europe has the highest number of novel CDR companies by location of corporate headquarters (180), followed by North America (161). Biochar is the most common type (136 companies) followed by Direct Air Capture (106) (CDR FYI, 2025). However, sizeable CDR potential exists across the world, which could be unlocked with investment, including from the range of market mechanisms as well as potential utilization prospects (Hepburn et al., 2019).

3. The outlook for CDR via carbon markets

Further incentive mechanisms are essential to scale CDR including the VCM and compliance markets (Burke & Gambhir, 2022; Edenhofer et al., 2023; Rickels et al., 2021; Rickels et al., 2022). This section canvasses the potential of such mechanisms.

The VCM has played a sizeable role in facilitating investment into CDR projects. This is particularly true for novel CDR, which have required new methodologies to be developed and tested, and for which there are limited other potential funding pathways. As this market matures, we can expect to see a shift from pre-purchases necessary today, to ex-post credit issuance and purchases in line with conventional CDR and other forms of carbon credits prevalent on the CDM. Insurance is also emerging which may spur the development of more confidence in CDR with regards to delivery risk as well as risk of reversal (UNFCCC, 2024a). Further standardization and regulation will be crucial to unlocking demand for CDR via the VCM. In areas related to voluntary corporate climate claims, frameworks such as the revised Oxford Principles for Net Zero Aligned Carbon Offsetting and the Integrity Council for the Voluntary Carbon Market's Core Carbon Principles have begun to guide buyers in the VCM on the role of CDR credits within organizations' voluntary decarbonization commitments (Axelsson et al., 2024; ICVCM, 2024). However, further efforts are needed to bring more consistency in this regard, as well as to improve quality safeguards related to the VCM, such as the protocols for monitoring, reporting and verifying (MRV) of carbon projects play an instrumental role (Smith et al., 2024; Burke & Schenuit, 2023). In any case, while CDR integration into national policies remains lacking in many respects, the VCM will likely continue to be important for CDR development, acting as a testing ground for new technologies as well as a means of leveraging additional demand. Should this trend continue, CDR will become a more prominent segment within the VCM.

Compliance markets can offer more demand certainty than a voluntary system and will thus likely play a key role in closing the CDR gap of 5–7 GtCO₂ that may be needed by 2050 (Smith et al., 2024). CDR integration into compliance carbon markets has in fact already occurred in some of the world's first generation of emission trading schemes. New Zealand, for instance, has integrated forestry-based CDR units into its emission trading scheme (ETS) since 2007 (Ministry for Primary Industries, 2023). Further integration of CDR into compliance markets could occur via two main routes.

One option is for CDR to be integrated into a compliance market by enabling all, or some of the compliance obligations to be fulfilled with carbon credits, as has occurred or is under development in several countries like Colombia, South Africa and Singapore (Fuss et al., 2024). This is often subject to quantitative and/or qualitative restrictions, for instance, putting a cap on the proportion of the obligation those credits can fulfil or restricting to certain types of credits. A second option is that CDR could be integrated directly into compliance markets as signalled by the United Kingdom and Denmark (ENDS Europe, 2024; HM Government, 2024). These schemes require active consultation from regulators and policymakers, to ensure that the necessary MRV processes are developed to facilitate the integration of high-integrity CDR in a way that does not interfere with ambitious

emission reduction efforts (Burke & Schenuit, 2023; Edenhofer et al., 2023). Yet true fungibility – whether different CDR types should be treated as equivalent to emissions trading scheme units or other forms of CDR – remains another ongoing challenge, as without it, there is a risk of mitigation deterrence and associated risks of greenwashing (Burke & Gambhir, 2022; Burke & Schenuit, 2023). Integration of CDR into such schemes thus necessarily involves varying levels of government oversight and intervention, ranging from direct government procurement (Rickels et al., 2022) and/or certification of CDR (Edenhofer et al., 2023). Still, such integration could garner much-needed funding for CDR.

UNFCCC-mediated international compliance market mechanisms under Article 6 of the Paris Agreement add a further dimension that could shape the market for CDR in future. Article 6.2, for instance, enables cooperation between governments to trade in mitigation outcomes generated from projects that either reduce or remove emissions, which can then be claimed within their nationally determined contribution (NDC) (UNFCCC, 2024b). Indeed, 78% of 168 Parties have expressed an intent to engage in at least one type of voluntary cooperation under Article 6 in their nationally determined contributions (A6IP, 2024). At COP29, instrumental rules guiding registry operations & guidance on standards and methodologies for CDR was concluded by Parties (Johnstone, 2024) paving the way for a convergence of standards and uptick in scale in turn under Article 6. As yet, the current ‘project pipeline’ under Article 6.2 does not contain any CDR projects (UNEP-CCC, 2025). However, this is likely to shift in future as Sweden and Switzerland have, for instance, indicated that they will pilot a transfer of novel CDR credits via the Article 6.2 framework (Swedish Energy Agency, 2024). Trade in both reduction and removal credits is also anticipated via the multilateral Article 6.4 mechanism overseen by the Article 6.4 Supervisory Body (UNFCCC, 2024c). However, as of January 2024 only 31 out of 760 projects that had expressed interest in the mechanism were removal based with only 2 of them being novel CDR (UNEP-CCC, 2025). The forthcoming compliance market for international aviation, CORSIA, is another market mechanism which could provide a pathway for funding CDR. The degree of differentiation between CDR and non-CDR project types, especially as it pertains to identifying and appropriate remedy reversals, will be critical to the success of the operationalization of the international market mechanisms under Article 6 and CORSIA (Delbeke, 2024). The IPCC’s methodological work to clarify the accounting of CDR in national greenhouse gas inventories will also be crucial in providing policy certainty and accountability.

4. Summary

While carbon markets have been part of the climate change mitigation toolbox for several decades, CDR has occupied only a small segment of them thus far. Of that share, while there is greater deployment of conventional CDR, it is novel CDR that has seen the most proportional growth in recent years. The latest market developments indicate a reinforcement of this trend, with novel CDR purchases in 2024 exceeded sales in 2023 with 75 percent following several large offtake agreements (CDR.FYI, 2025).

It is evident that voluntary, as well as domestic and international markets stand to shape demand for CDR in future. To make these levers more tractable, three cross-cutting developments are needed:

- (1) Mechanisms need to clearly distinguish between different forms of climate mitigation outcomes both between novel and conventional CDR, and CDR compared to emissions reduction and avoidance;
- (2) Mechanisms need to ensure the quality and integrity of CDR through careful MRV and corresponding certification, taking into account issues such as additionality, risk of reversal, and accountability measures to address reversals;
- (3) Actors need to identify the synergies between domestic and international carbon markets, and how they can apply in an additive manner complementary to a particular national or regional setting and/or policy landscape.

Robust differentiation between CDR and emissions reduction and avoidance projects, as well as between CDR types is vital in leveraging the power of market mechanisms to scale CDR by unlocking new demand and directing financing to where it is needed most (Burke & Gambhir, 2022). In line with this, and emergent pressures that are leading to a flight to quality, there is evidence of a resurgence in interest amongst actors

to establish better standards, including as a means to integrate CDR into compliance markets, either directly or via recognition of CDR-based carbon credits. The emerging Article 6 regime under the Paris Agreement will also shape this landscape, given its notable role in helping countries meet their nationally determined contributions. Carbon markets could play an instrumental role in closing the CDR gap (Fuss et al., 2024) if they sufficiently distinguish between the CDR and other forms of mitigation outcomes, uphold quality standards and are tailored sufficiently to the domestic & international policy context. Ultimately, the future of CDR in carbon markets hinges on the clarity and rigour with which we differentiate, define, and enforce these mechanisms within a rapidly evolving policy landscape.

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Disclosure statement

R.H. is a co-founder of CDR.fyi and owns Marginal Carbon AB (consultancy in climate policy and carbon removal). No other conflicts of interest exist. N.W. is a Policy Manager at DVNE (Deutscher Verband für negative Emissionen = German Association for Negative Emissions) and a collaborator at CDR.fyi.

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