Carbon Dioxide Removal (CDR) Evidence Review

An overview of CDR and bottlenecks to overcome

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Abstract

The carbon dioxide removal (CDR) industry is nascent, yet scientists agree that it is necessary for net zero. There are huge challenges to address in order for the industry to reach its intended scale. In this report, we explain and discuss the bottlenecks that should be unblocked to accelerate the growth of a new, trillion-dollar CDR industry.

The key and intertwined barriers impacting the development and deployment of CDR approaches are:

- low technological and commercial readiness,
- financing,
- the regulatory environment, and
- lack of political support or awareness.

In this report, we will discuss these bottlenecks. First, we will introduce **what CDR is**, why we need it, and what we know and don't know at this stage. Then, there will be a discussion about why **demand must be created for CDR** in order to resolve the financing bottleneck to drive step-change in lowering other barriers. Policy is discussed as a mechanism to fund technological progress, stimulate demand, and develop fit-for-purpose regulation for this emerging industry. Better monitoring and reporting and verification (MRV) approaches are also required to quantify the efficacy and (un)certainty of some CDR methods, which in turn affects their credibility in markets and the regulatory context. Therefore, we explore the challenges and interplay between MRV and regulation.

Additional financing is sorely needed because the resource and infrastructure requirements of CDR can be immense. For projects to succeed, we also need the support of a diverse range of stakeholders, including governments and communities. At the moment, **public sentiment** toward certain approaches is not consistently favourable, partly due to a lack of available and trustworthy information resulting from silos and commercial interests. **This review concludes by identifying cross-cutting bottlenecks that could be addressed for the CDR industry to progress.**

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Introduction to CDR

Carbon dioxide removal (CDR) refers to any mechanism that can remove carbon dioxide (CO_2) from the atmosphere. CDR approaches are not optional or 'nice to have'; they are the "net" in net zero in that they bridge the gap between hard-to-abate industrial emission reductions and the CO_2 levels we require to limit global warming to within 1.5-2°C [1]. CDR is also the only means of removing legacy emissions. The 2022 sixth assessment of the Intergovernmental Panel on Climate Change (IPCC) Working Group III confirmed that CDR is an essential climate solution; the overwhelming majority of IPCC mitigation scenarios that limit global warming to below 2°C assume the use of CDR [2], [3]. By 2050, Paris-consistent scenarios suggest annual removal rates of 7-9 billion tons (Gt) of CO_2 need to be removed from the atmosphere per year (see **Figure 1** and note the large uncertainties in the min/max bounds, and the fact that most of this carbon removal comes from so-called 'novel' CDR) [4], [5]. The concentration of CO_2 in the atmosphere is at an all-time high of 417 parts per million [6]. That's about 0.04% of what we call 'air'. It is therefore very difficult and correspondingly costly to do CDR. At a cost of hundreds of dollars per ton CO_2 removed, this means that a trillion-dollar industry is being built from scratch [7].

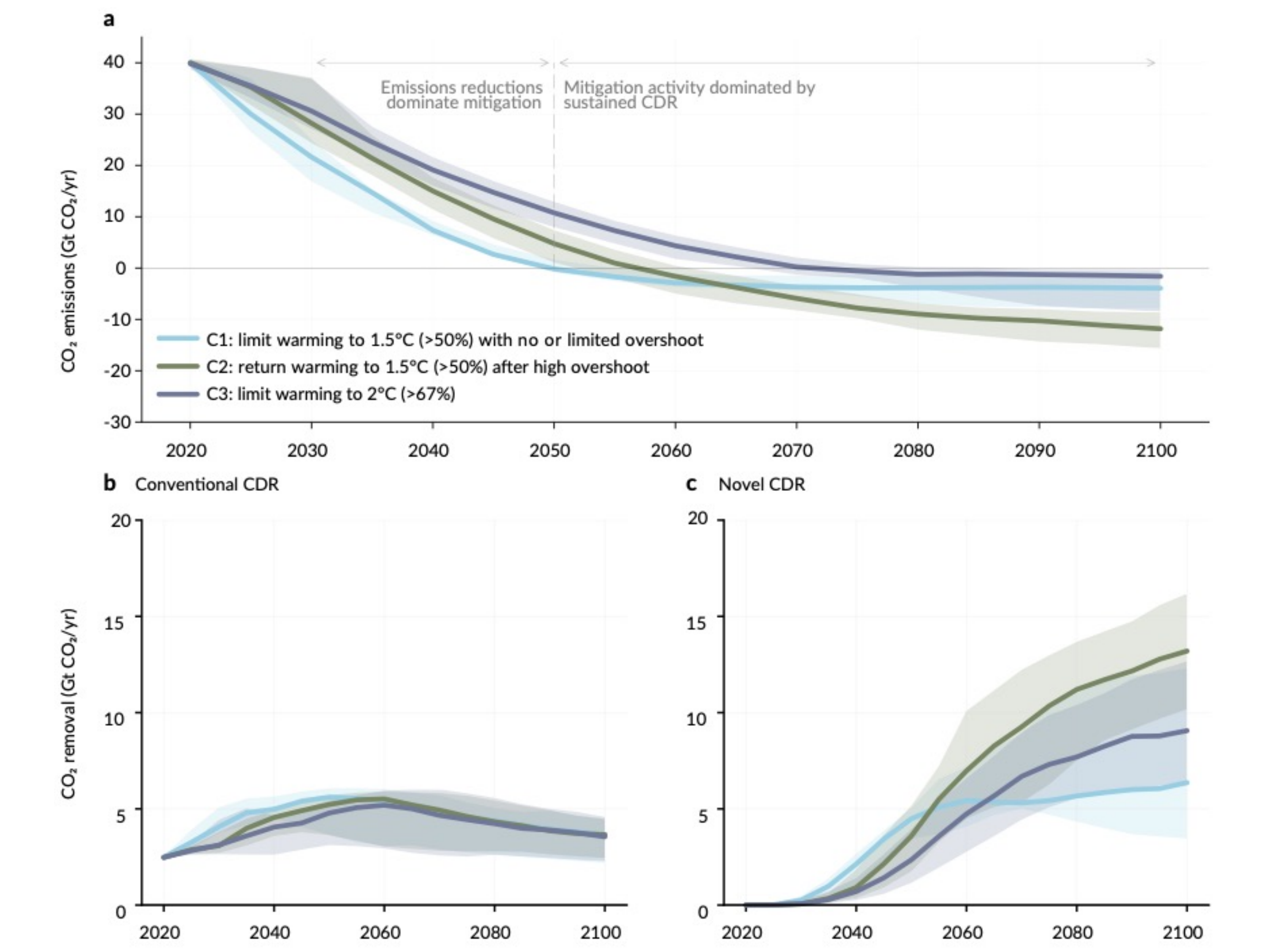

Figure 1. Graphs showing median and interquartile ranges of (a) CO_2 emissions and (b, c) the required CDR capacity for three sub-2°C global warming scenarios. Conventional CDR on land refers to techniques such as reforestation. In the novel CDR graph (on the right), only direct air capture with carbon storage, bioenergy with carbon capture and storage and enhanced rock weathering are included. Image from N. Vaughan *et al.*, 2024 [5].

It is scientifically, environmentally and economically more effective to avoid a ton of emissions than it is to remove it from the atmosphere [8], [9]. CDR should therefore not be used as an excuse to continue with business as usual. It is not a substitute to initiatives targeting deep decarbonisation; net negative emissions technologies should only be deployed to compensate for residual emissions after abatement, or as a means of addressing legacy emissions [8]. Although often confused, CDR is not the same as industrial carbon capture and storage (CCS), which is a set of processes that remove CO_2 from industrial fumes (to varying degrees of efficiency) to prevent it from entering the atmosphere. Carbon capture techniques (CCS) are considered decarbonisation technologies. Also, projects that remove carbon dioxide from the air cannot claim to be 'CDR' without evidence that the removals would not have otherwise happened (also called 'additionality'). For example, if an afforestation project claims to remove carbon from the atmosphere, there needs to be proof that without intervention or the incentive of carbon credit generation, the area would remain unforested for the duration of the project [10].

CDR approaches can be segmented in many ways. One common classification is nature-based/conventional CDR versus novel/technological CDR. However, this classification can be unhelpful because it makes it seem as though nature-based CDR does not require technology, or vice versa, and that technological CDR does not involve nature. These are both incorrect assumptions. At the moment, nature-based CDR (or land-based CDR, e.g., afforestation or regenerative agriculture) accounts for around 99% of carbon removals. This is not the only way to divide CDR techniques; some people distinguish 'open' and 'closed' system CDR according to how much of the process occurs in the bio- or geo- sphere, and a recent RMI report classifies CDR into three mechanism-dependent groups: biogenic, geochemical, and synthetic (**Figure 2**) [11]. The RMI report further sets out the different pathways to scale for 32 CDR approaches, which supports other literature that suggests the next decade is critical for CDR to scale appropriately. **Figure 2** also shows that carbon dioxide storage is often a modular addition to CDR. This is useful because many CDR techniques generate gaseous or supercritical streams of CO_2 that must be sequestered in an inert form to (reasonably) prevent its re-release into the environment. Common examples of 'durable'[a] CO_2 storage are: (a) burying it by injecting CO_2 or biomass underground, subjecting it to mineral or physical trapping, or (b) converting CO_2 into carbonates or bicarbonates that are stored in rocks or the ocean. The durability of carbon storage has an impact on the quality of CDR and the cost of sequestration. Projects with higher risk of CO_2 release (for example, for afforestation, a wildfire would trigger a catastrophic reversal of CDR) are often cheaper than durable ones.

This review does not go into the distinct needs for each CDR pathway but occasionally uses examples and generalisations to illustrate the need for support. Also, this review intentionally does not include methane or other short-lived climate pollutant (SLCP) removals. Due to the atmospheric lifetimes of other pollutants, whether other greenhouse gas removals are required is a separate scientific question that overlaps with QCF's SLCP strategy. Policy improvements for CDR mentioned herein may benefit the removal of other climate pollutants, but this is not the focus of this document.

[a] There is no widely acknowledged definition for 'durable' in the context of CDR, but the term refers to the planned duration of carbon storage – ideally >100 years to reduce peak warming (this is the definition that XPRIZE and Microsoft use, although Frontier Climate and UNFCCC use >1000 years).

Known CDR approaches fall into three groups, based on their key input. Storage of captured CO_2 is a fourth, separate domain.

CDR term:	Biogenic CDR	Geochemical CDR	Synthetic CDR	Storage of CO_2
Definition:	Biogenic CDR (bCDR) approaches use naturally-occurring biogenic carbon fixation mechanisms to capture CO_2 from the atmosphere. The most important of these mechanisms is photosynthesis.	Geochemical CDR (gCDR) approaches use naturally-occurring neutralization reactions between acidic forms of carbon and alkaline minerals to convert CO_2 from the atmosphere into solid carbonate minerals or dissolved bicarbonates.	Synthetic CDR (sCDR) approaches use engineered systems powered by low carbon energy to directly separate CO_2 from the air and capture it or to alter water chemistry to indirectly remove CO_2 from the air.	Storage of CO_2 approaches store captured and concentrated streams of CO_2 through trapping, mineralization, or other physical or chemical processes.
Key input:	**Sustainable biomass**	**Alkaline materials**	**Low-carbon energy**	**Suitable sites for CO_2 storage**
Implications for scaling:	• The potential scale of bCDR will be bounded by the availability of sustainable biomass feedstocks. • The most competitive bCDR solutions, long run, will be those that source and transform available biomass inputs into durable CDR most efficiently.	• The potential scale of gCDR will be bounded by the availability of alkaline mineral feedstocks needed for neutralization reactions with carbon. • The most competitive gCDR solutions, long run, will be those that can source, process, transport, and dispose of alkaline minerals for CDR most efficiently.	• The potential scale of sCDR will be bounded by the availability of low carbon energy. • The most competitive sCDR solutions, long run, will be those that can transform low carbon energy into CDR most efficiently.	• The potential scale of these approaches will be determined by access to suitable storage sites. • The most competitive storage solutions, long run, will be those with the lowest cost to establish and operate.

Figure 2. Classification of known CDR approaches from the RMI's Applied Innovation Roadmap for CDR [11]. The process of CDR separates CO_2 from the atmosphere, but carbon storage technologies are also required to achieve durable carbon removal. Usually, the term 'CDR' assumes the storage component because otherwise the CO_2 would be re-released.

Technological knowledge gaps that surround CDR

We do not know how much CDR we will need, although estimates agree that somewhere between five and ten billion tons (Gt) of CO_2 will need to be removed every year by 2050 to limit global warming to less than 2°C [2]. Due to a lack of information and the low technological readiness levels of many types of CDR, most IPCC models understandably rely heavily on relatively familiar techniques: bioenergy with carbon capture and storage (BECCS) and direct air capture with carbon storage (DACCS), which are used as stand-ins for CDR [12]. Mathematically, stabilising global temperatures requires CDR to compensate for any residual CO_2 emissions after industrial decarbonisation. However, there is deep uncertainty around both the realistic potential for CDR and what level of residual emissions will exist by mid-century [13], [14], [15]. However, we know that some sectors, such as long-haul aviation, will be difficult or impossible to completely decarbonise, so it seems reasonable to plan for CDR given that a technological ramp-up is required to achieve CDR deployment at scale [4]. We expect to need a portfolio of different CDR techniques because it is unclear which approaches have the potential to scale, and because different geographies have different regulations and resources available. It is likely that only a few approaches will be able to reach multi-gigaton scale within a meaningful time frame. Despite this, of the $4.1bn in public funding that has been spent on novel CDR in the US, $3.5bn has been dedicated to developing four direct air capture (DAC) demonstration hubs [2]. Still, there remain well-documented technological knowledge gaps hindering the progress of most CDR technologies.

We know that the chemical processes underpinning the removal of CO_2 from the atmosphere work; they were discovered decades ago but have not been pursued as an industry until now. However, **we don't know how to remove CO_2 at scale in the most efficient and effective way** (although as mentioned previously, the exact processes will vary by location). While the actual science of CO_2 removal is often not patentable, the process designs of many CDR methods are. For this reason, the learn-build-test cycle of CDR (and its relevant political support mechanisms) is happening slowly. There is very little consistent, transparent, accessible data regarding the optimisation and/or implementation of novel CDR approaches such as DAC or marine CDR (mCDR) at the moment [16]. This might be a bottleneck for decision-making in the future.

We do not know how durable or scalable all types of CDR are. In some cases, such as for most open-systems CDR, the foundational science and baseline data are missing. This prevents people concluding whether a CDR approach is working in a given setting. The knowledge gap does not look the same for all CDR approaches – e.g., for some of the proposed mCDR methods, the feasibility is not yet established because there is a lack of foundational science required to measure net CO_2 removal (please see the RMI's Applied Innovation Roadmap for CDR to learn more [11]). A prime example of a CDR approach with missing foundational science is ocean alkalinity enhancement, which is subject to various feedback loops that can result in the release of CO_2 over time – this will be expanded upon in the 'Underdeveloped Monitoring, Reporting and Verification' section. Yet other types of CDR have a strong evidence base for CO_2 removal but are affected by process economics and the availability of local resources.

Uncertainties also exist around some CO_2 storage methods. Removed CO_2 must be stored in a thermodynamically stable form to avoid its re-release into the atmosphere. While scientists have high confidence in the durability of some carbon storage methods, such as geologic carbon storage, less is known about the effectiveness of other methods and their scalability, such as in situ mineralisation [17]. Another open question surrounds the effectiveness and durability of bicarbonate storage in the ocean, which is dependent upon many variables including the type of alkalinity introduced, ocean conditions, biological activity, and so on [18]. The case is the same for burial or sinking of carbon-containing materials. That is because the carbon could be re-released into the atmosphere through a combination of decomposition and expected (e.g. ocean circulation) or unexpected (e.g. burial pit degradation) dynamics associated with the storage site. As mentioned previously, the risks of reversal affect the financial and climate repair value of CDR [19]. Therefore, understanding the effectiveness and durability of carbon storage is important; temporary storage is only a temporary solution, and variations in carbon removal efficacy and durability impact the long term estimates of how much CDR we need.

Technical knowledge gaps need to be addressed with more research and development across the board, bearing in mind the large knowledge asymmetry that exists across CDR techniques and potential locations. An analysis of the scientific literature on CDR shows that the field is nascent, but papers are proliferating exponentially [2]. We know a lot about certain CDR approaches; at present, CDR research is dominated by non-proprietary nature-based CDR methods such as afforestation/reforestation[b] and biochar, some of which are already deployed at scale and therefore have relatively little growth potential (refer to **Figure 1**) [2]. Very little scientific and patenting activity is being generated in Africa and South America, even though objectively there are good resources for CDR in these locations (e.g. industrial alkaline waste for CO_2 sequestration, low carbon energy) [21]. Publicly (or philanthropically) funded research, development and demonstration projects are a critical lever to increase the availability of trustworthy data and to improve awareness, acceptance, and uptake of CDR projects. Specifically, more research and development funding should go to actors working on the development of novel and scalable CDR approaches (or baselines for those approaches). Whether those researchers are commercial or academic, they should share their data in a transparent way and ideally have the capacity to progress to demonstration studies.

[b] Note that afforestation and soil carbon sequestration should only be considered CDR methods when there is clear additionality – i.e., when it is clear that the given project provides a net increase in terrestrial carbon stocks [20].

Lack of demand for CDR

CDR fundamentally has no inherent value (unless the end product is a pure stream of CO_2 that can be used in a durable product such as concrete, or used to produce e-fuels, but this is currently expensive), and so demand must be artificially created to scale the industry. While some private sector actors are buying CDR today, novel CDR with higher durability is costly and in short supply. In this section, we will identify important levers that could stimulate demand for CDR.

Who is buying CDR now?

At the moment, CDR is quite expensive and highly profitable companies are purchasing removal credits out of a wish to see the industry as a whole expand - either altruistically or for business reasons [22]. To date, just over two billion dollars have been spent on theoretically removing five million tonnes of CO_2 [23]. Generally, the price of CDR is correlated with: (i) the cost of extracting CO_2 (including possible material transport etc), (ii) the cost of measurement, reporting and verification (and thus the measure of uncertainty in a method, see later), and (iii) the durability of the storage method.[c] Therefore, the price of CDR is highly variable, with DAC costing over \$1000/tCO_2e on average according to the reporting platform CDR.fyi, whereas BECCS sells for \$100-300/tCO_2e. Carbon removal credits are being purchased on the voluntary carbon market (VCM) by businesses trying to reduce their emissions according to the science-based targets initiative (SBTi) standard. Because the price of CDR is high and confidence levels in both the CDR approaches and the integrity of the market are low, the sectors that are engaging in the VCM now are the highly profitable but low emitting sectors (such as information technology providers and the financial services), which are typically diverting less than 1% of profits towards CDR purchases [22], [23]. Microsoft is at the top of the leaderboard, having bought over 2.8 million tons of carbon removal in a single (pre-) purchase via Frontier in 2023.

Frontier's platform illustrates how important it is to guarantee demand for CDR. Frontier is an initiative launched by Stripe, Alphabet, Shopify, Meta and McKinsey, that provides legally binding advance market commitments (AMCs) for carbon removals.[d] The aim is to aggregate demand for CDR approaches that pass Frontier's key criteria, thereby (i) enabling CDR start-ups to make a business case for scaling up, (ii) increasing supply of CDR, and (iii) reducing barriers to entry by performing due diligence centrally [25]. Similar efforts to Frontier have been launched, such as NextGen CDR Facility.

There are other opportunities to catalyse demand from the private sector. For example, SBTi does not currently provide guidance on how to incorporate CDR into net-zero plans – something that many stakeholders hope will change in 2024 [26]. A science-based and robust SBTi guidance could be instrumental for CDR demand by giving corporate players more justification to enter the voluntary carbon market (VCM) and right-size CDR within corporate climate action. The lack of intrinsic value means that the private sector at large would only commit to CDR if policy mechanisms are in place. There is a need to create policy mechanisms to help bring CDR costs and prices down, increase trust, and make emissions more expensive.

[c] There are uncertainties regarding the durability of various CDR methods, to be discussed in the next section: Underdeveloped monitoring, reporting & verification.

[d] The concept of an AMC was proposed in 2005 by economist Michael Kremer at the Center for Global Development [24]. The first successful AMC was created by Canada, Italy, Norway, Russia, the UK and the Bill & Melinda Gates Foundation to guarantee demand for a pneumococcal disease vaccine that is projected to save the lives of millions of children by 2030.

In fact, the integrated assessment models that allow the IPCC to conclude that CDR is required assume that (i) CDR gets cheaper in the second half of this century (usually the assumption is $100/t$CO_2$)[e], and (ii) carbon pricing makes emissions more expensive [15].

[e] The $100 per ton benchmark is commonly used and was (apparently) chosen as a value that makes CDR economically feasible at scale [27]. It might be appropriate for BECCS, which is the CDR method that the IPCC models 'choose' first. However, there is little evidence to suggest that effective, durable carbon removal can cost as little as $100/t$CO_2$e – in a 2024 CDR.fyi survey of 91 suppliers, only 31% reported hitting that target today, but two-thirds of those companies were founded within the last three years, so whether or not the business survives is another story [22]. In fact, the $100 per tonne benchmark itself is interpreted differently by people: is it the break-even point to the seller, cost to buyer, or cost post-government incentives? [26].

Policy is a tool for creating demand

High emitters are not currently paying for CDR, and it is more important and overall cost-effective that they focus primarily on decarbonising. However, these industries (such as cement and mining) are more likely to also have residual emissions that should be removed using CDR. Since the scale-up of CDR is highly capital intensive, profitable yet hard-to-abate industries should ideally contribute to those costs. Policy needs to support this by creating compliance demand from such companies, or taxing emissions to pay for public procurement of CDR in the interests of public good. While the private sector and VCM can be catalytic, a report by CarbonPlan revealed that most stakeholders think the long-term solution to the problem of scaling CDR is public sector demand [26]. An example of how this could be done can be found in the US Department of Energy's (DOE's) CDR Purchase Pilot Prize, which has signalled a $35 million intent to purchase CDR on the behalf of the public [28]. Alternatively, placing a price on emissions such that it is much cheaper to decarbonise operations as compared to (a) business as usual or (b) carbon removal could be very effective, but that is a whole field of study that cannot be summarised in this review. The existing policy landscape will be discussed in the following sections, but please note that market shaping policy mechanisms are just one possible policy instrument for supporting CDR.

There are some outstanding issues that could prevent CDR from being eligible for carbon markets. In the VCM, which is often cited as a template for what a carbon removal compliance market might look like in the future, there is confusion over what kind of information is needed to ensure that CDR is credible. The key bottleneck is a lack of foundational science underpinning monitoring, reporting and verification (MRV) of projects, particularly for CDR methods that depend on nature, such as enhanced rock weathering and marine CDR. A joint report by Shell and Boston Consulting Group (BCG) identified a reputable MRV framework as being the most important criterion for purchasing. Indeed, 91% of buyers rank MRV as the top consideration in credit purchase decisions because the added transparency (a) helps them gauge quality and (b) reduces the reputational risk of buying poor quality carbon removals [29]. The recent CDR.fyi survey also showed clearer standards for quality verification alongside cost per ton as being the most important factors that buyers consider when purchasing [22]. Nevertheless, this buyer perspective on MRV is not reflected in a carbon credit's monetary value which significantly reduces the ability to deliver said transparency. (That said, Frontier are pushing to have project developers break down MRV costs in future [30].) Better MRV could unlock demand from the private sector in the short term as well as provide an evidence base for policymakers to justify and improve public sector demand for CDR.

Underdeveloped monitoring, reporting & verification

MRV confirms that customers are getting what they paid for: CO_2 removal and storage. As such, MRV is essential to answer the obvious questions that make carbon credits trustworthy and underpin market standards: "when?", "how much?" and "how long for?" [30], [31]. MRV should be a standardised procedure to provide justified, comprehensive, and quantitative estimates with respect to the net carbon removed by a CDR project [32]. The outcome should be a number of tons of carbon removed from the atmosphere for a certain duration, with an associated measure of uncertainty. Ongoing monitoring is required to account for any carbon leakage back into the atmosphere to inform liability assignments. To avoid conflicts of interest, MRV data should be auditable by a third-party verifier – however, the state of the CDR verification ecosystem, which includes CDR verifiers, is complex [30], [33], [34]. The creation of a collaborative learning loop where all participants can access MRV results and best practices could be very valuable for the CDR industry [30].

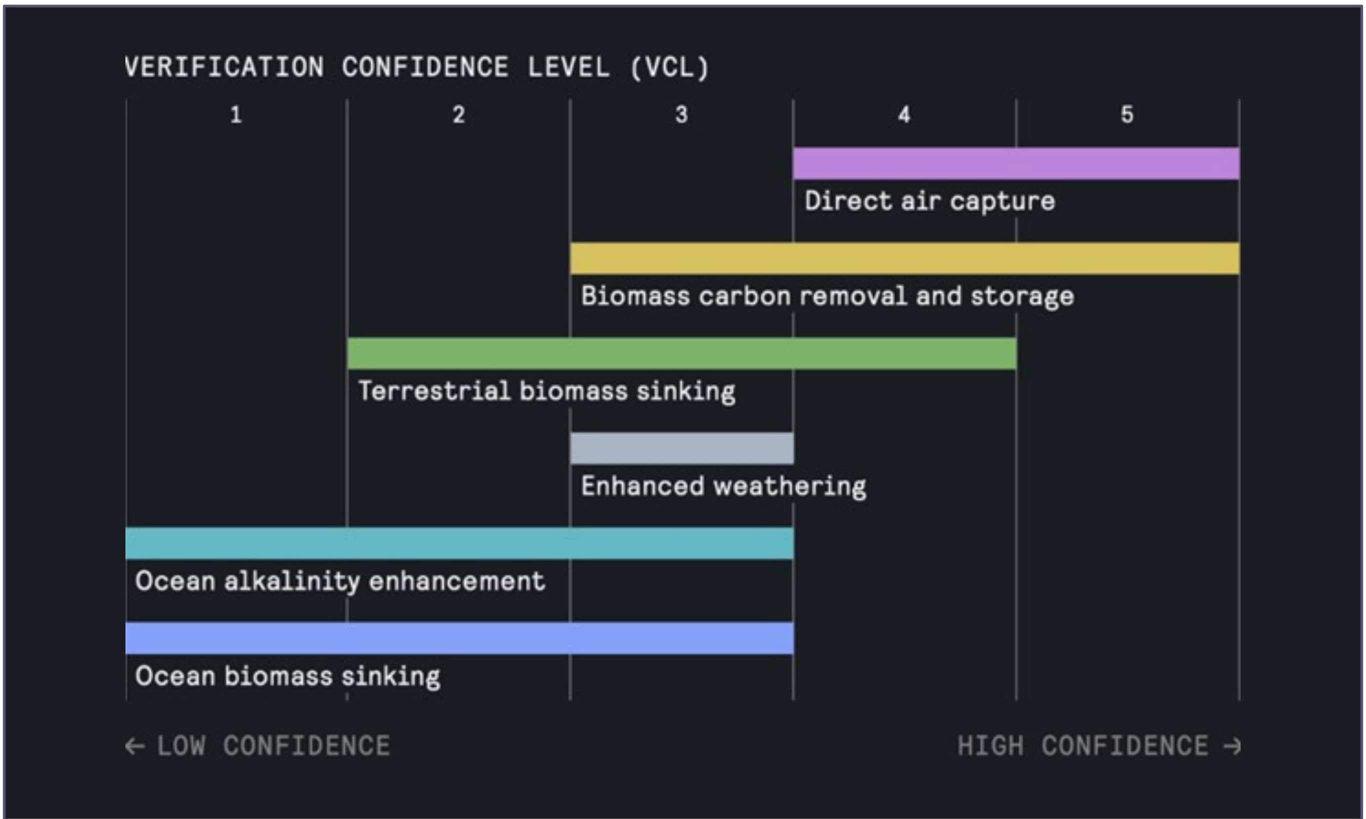

Figure 3. Indicative illustration of the uncertainty in different CDR methods. It's important to note that there are extremely large, fundamental uncertainties in whether some CDR methods work – especially for open system CDR. Image from CarbonPlan's CDR Verification Confidence report for Frontier [31].

As a concept, MRV is becoming confused because the term "MRV" means slightly different things to different people; scientists zoom in on the measuring the efficacy of a CDR approach, whereas market-focused people are focused on verification that protocols are being adhered to [35]. In addition, the MRV process is being conflated with lifecycle assessments (LCAs) and environmental impact assessments (EIAs). In fact, Frontier and CarbonPlan's verification framework require sellers to perform a 'total carbon removal' measurement which is obtained by taking the net CO_2 removed (MRV information) and subtracting carbon emissions from materials, energy demands, and secondary impacts of that energy demand (traditionally LCA or EIA information) [31]. The reason for this is that buyers of CDR want: (i) a holistic view of the net carbon drawdown not only from the CDR method, but also when accounting for the whole supply chain (LCA), and (ii) information regarding the co-benefits or risks to humans and nature (EIA). The CDR.fyi survey of 27 purchasers show that 33% consider co-benefits to people and/or nature when prospecting a CDR purchase and 46% consider the proven safety of the method – although it is important to note that today's voluntary buyers have different motivations than the intended buyers of the future [22]. This data is necessary for stakeholders (buyers and sellers, local communities, policy makers) to fully evaluate the pros and cons of CDR methods [36]. However, premature, pre-implementation LCAs and EIAs (not informed by empirical data) could be risky because they may present another barrier to demonstration and commercialisation. Although LCAs and EIAs are iterative and scale-dependent, if start-ups are required to perform and submit LCAs or EIAs at the research and development stage – before the technologies have been optimised – any less-than-optimal results may prevent certain types of CDR from scaling, especially those that benefit from economies of scale or extensive data collection. Also, the lack of baselines for open system CDR means that controlled EIAs are unrealistic, so the high standards for pilot projects may create a barrier to experimentation. The best example of how stakeholders' appetite for data can affect a project is Planetary Technologies's mCDR mesocosm studies in Cornwall, England, where a vocal local opposition demanded: independently verifiable standards, extensive baseline data of the ecosystem for perturbation monitoring/ecosystem impact studies (i.e., EIAs), MRV protocols and regulation [37]. Whilst these are valid requests from communities, this example was Planetary Technologies's first pilot – a medium-scale experiment that had been fully approved from a regulatory standpoint, with the aim of collecting project and ecosystem data.

Currently, project developers often have to create their own MRV methods alongside their CDR project out of necessity. This can be expensive and unprofitable, especially for open system CDR which requires extensive data and observation to generate baselines to prove additionality. As mentioned earlier, CDR can be categorised into open and closed system approaches, and this is a useful classification for MRV considerations because closed system CDR methods like DAC are generally observable and measurable. However, the same cannot be said for open system CDR because of ecosystem interactions and large spatial and temporal scales [38].

Open system approaches, such as enhanced rock weathering or ocean-based approaches, have a larger scale potential due to lower energy costs and a reliance on nature to enable the reaction, but are inherently variable and difficult to measure because of dispersion in natural open systems over large timescales (~years) [38]. Because of this, the number of tons of carbon removed via a certain CDR method is typically only an estimate, and one that depends on imperfect assumptions (e.g., the rate and extent of ocean carbonate formation, which is location-dependent). In addition, while existing MRV strategies have focused on the project-level quantification of outcomes, open system quantification needs to account for potential secondary effects beyond the scale of a single project developer. This requires robust, accessible, and standardised baseline data – the foundational science is missing. Hence, MRV is not a straightforward problem to solve for CDR, and it requires nuanced differentiation between open and closed system approaches. Arguably, open system MRV is the more difficult one to solve, requiring both hardware and software approaches.

Many MRV approaches, in particular for open system CDR, rely on computational modelling for the following reasons:

1. carbon removal in open systems can happen far from the site of direct intervention both in space and time;

2. the effective magnitude or perturbation will be small in comparison to the natural variability of these systems;

3. the impacts of CDR (positive or otherwise) could be non-linear and/or delayed; and

4. vary with respect to severity and extent according to, for example, weather patterns, tides, albedo etc.

A large focus, both financially and intellectually, currently lies on making computational models fit-for-purpose and validating them against real deployments (of which there are few). If the primary objective of MRV is to deliver an assessment of additionality and durability, any protocol or model for an open system must assume – and monitor – several ideal conditions to gain an overall estimate of carbon flux (e.g., no inorganic or biologically-mediated precipitation in the case of ocean alkalinity enhancement[f]) [39]. Moreover, models require a sophisticated baseline construction of these highly variable systems, which to date often do not exist – especially true in soils and the ocean. This means that it is difficult to prove that 'additional' carbon is stored in either of those places, leading to net negative CO_2. Uncertainty remains both around what data would be needed for rigorous baselines, as well as how that data could efficiently be collected. Furthermore, people would like to extend these models to account for externalities or the counterfactual (e.g. changes in ocean currents if global warming does not stop at 1.5°C), which is important but would require extensive data collection that is not incentivised or rewarded in the current MRV status quo.

[f] Precipitation of bicarbonate in the ocean releases gaseous carbon dioxide: $Ca^{2+} + 2HCO_3^{-} \rightarrow CaCO_3 + H_2O + CO_2$

Hardware for MRV

For open system CDR, the availability of fit-for-purpose tools, such as sensors and suitable platforms, is a major bottleneck to creating baselines and validating models [36]. Technological advancements in carbon measurement and associated parameters at scale, such as alkalinity in marine contexts, are long overdue and require a foundational science approach. Some CDR techniques, especially soil- and ocean- based CDR methods, shine a light on the lack of major innovations in scalable monitoring tools and/or their accessibility. In some cases, the necessary equipment for these measurements exists, but it can be prohibitively expensive, so little of it exists beyond the academic scientific community. Consequently, measurement tools are typically not designed for commercial scale-ups that require cheaper equipment that may be less precise but more scalable. A few start-ups attempted to tackle this problem in different ways, but none have significantly scaled or entered field trials with meaningful contributions; some even failed (e.g. Submarine). Because of this, there is a strong sense of doubt from investors but also other market practitioners around the profitability and integrity of for-profit MRV approaches. Therefore, accelerating the development of models, tools, and methodologies is currently largely a non-profit effort. This may be a good thing, because MRV performed in the non-profit or academic setting is less prone to criticism and bias. Recently, the US DOE took the encouraging step of issuing a $15 million prize to support national labs improving MRV practices for CDR [40].

Interplay between MRV & governance

In addition to scientific gaps, there are gaps around MRV governance that merit careful attention in the near term as they will establish precedents for how the CDR sector will develop. For example, MRV both informs and is fundamentally shaped by how we define 'a ton of CDR'. That definition is both technical and normative, and there is field-wide ambiguity about what counts as CDR [41]. More work is needed on how different funding mechanisms for CDR present different requirements for what rigorous MRV should look like – and how MRV could be standardised [42]. Further clarity is missing around whether MRV costs are added on top of a credit price and handed through to the buyer, thus becoming a somewhat dynamic tax, or whether it must be included in an agreed total price per ton and covered by the project developer, regardless of the actual equipment and operational cost. There is an opportunity to create an independent set of enforceable standards (for each CDR pathway) to ensure that CDR MRV produces consistent, transparent, trustworthy results [43].

Need for more political support

The role of policy in ramping up CDR is multifaceted. Governance can create an enabling, supportive environment for CDR projects; it funds research and development, defines standards, supports markets, ensures equity and oversight, and can help build public confidence in the industry. Ergo, effective policies for CDR could address many, if not all the problems mentioned in this document under the current CDR ecosystem. This is supported by the modest projections of voluntary purchases in the 2030s-2040s, which suggest that the public sector must become a major source of demand for CDR [44]. However, CDR is rarely explicitly mentioned in net zero emissions targets, although relevant policies are being developed in the EU, UK, and the US [2]. Scaling CDR at pace will not be possible without forward-thinking, sustained industrial policy that aims to build a CDR ecosystem while not allowing the prospect of CDR to disincentivise much-needed decarbonisation of industry [45], [46].

Generally, policy serves three primary purposes for CDR (also sometimes called greenhouse gas removal; GGR in the policy context):

i. **Stimulate strong demand** to pull CDR approaches into commercial reality. This could be done through public procurement schemes, through compliance mechanisms [47], by embedding CDR into emissions trading systems (ETS) [15], or via demand-side subsidies such as tax incentives or carbon contract for differences (in which the government pays the difference between CDR costs and an agreed reference price). Demand was discussed in the section 'Lack of Demand for CDR'.

ii. **Set standards for a regulatory framework** that right-sizes CDR with respect to decarbonisation (i.e. through separate removal and mitigation targets) and encourages market activity, investment, and entrepreneurship. Clarity in legal frameworks that deal with reporting and accounting criteria, and safeguards to manage social and environmental risks are essential. There should be active public engagement and consultation to make sure that CDR developments proceed in line with societal priorities.

iii. **Create an enabling environment** for CDR. This means that governments need to de-risk CDR sufficiently for buyers to engage with the newly created markets. High infrastructure costs are a barrier to first-of-a-kinds but there is also a need to fund more fundamental research. Skills gaps and other resource limitations also need to be addressed. These barriers to scale can be addressed by providing capital subsidies, research funding and by creating industrial clusters with shared infrastructure and vocational training.

The state of government support for CDR

A portfolio of CDR technologies is required for net zero, but current policy mechanisms favour nature-based CDR or biological CDR and are under-resourced to deliver a portfolio of CDR techniques [48]. To date, $4 billion has been committed by governments to CDR research and demonstration activities, with the majority ($3.5 billion) of that happening in the USA. In the debate about government finance for CDR, public sector investment into solar technologies is often invoked as a comparison, to show how little attention CDR has received and to persuade people that CDR investments would lead to a massive decrease in cost. Due to governmental support, the technology for photovoltaics was developed and then deployed in the early 2000s. The price of solar panels subsequently decreased rapidly – to the tune of 20% for each doubling of capacity [49]. Governments heavily subsidised solar early in its development, but a BCG report suggests that investment in 'durable' CDR is only approximately 10% compared to the equivalent early stage of photovoltaics [44]. Crucially though, photovoltaics (i) produce energy and therefore have market value (even if demand was slow to take off), and (ii) are a much more tightly defined technology class than CDR. Therefore, assuming that CDR costs will decrease in an analogous manner to solar is inaccurate and unhelpful [50].

Internationally, of the 62 long term low emission strategies submitted to the UN Framework Convention on Climate Change, 26 have indicated an interest in using novel CDR45. Rarely do policies explicitly mention novel CDR [51], but CDR-specific support mechanisms are in place in the US and to a lesser extent in Sweden (through BECCS auctions), EU, and the UK. Typically, the policy focus is on approaches that have worked for the countries and regions: the US focuses on CDR tax incentives, the EU on setting targets for CDR in the European Climate Law, and the UK is looking at applying contracts for differences to CDR, as it did for wind energy. However, policymakers' lack of technical and empirical understanding of CDR threatens the development of appropriate and right-sized support mechanisms. For example, most of the US government's support for CDR goes towards direct air capture. Some argue that this is proportionate, yet others think that more inclusive laws will allow for faster future evaluation of a broad portfolio of CDR pathways, some of which may not currently exist. It is extremely important for political early movers to get CDR support mechanisms right because these policies shape antecedent decisions in those countries, and indeed in other countries [2].

The United States of America. The US recognises the need for CDR in its nationally determined contributions (NDCs) and national climate assessments (NCAs), bolstered by significant modelling analysis at the national and sub-national level [52], [53]. The USA has the most ambitious CDR policy in the world with bipartisan political support. The landmark 2022 Inflation Reduction Act (IRA) expanded an existing tax credit programme, 45Q, which was originally intended to support sub-surface injections of CO_2 for enhanced oil recovery and carbon sequestration. Two crucial tweaks have been made to 45Q that render it appealing for DAC companies: firstly, the volume requirement has been reduced to 1,000 tCO_2/year, and secondly, the value of the tax credit has increased to $180/t for DACCS only (and not other types of CDR) [2].

In 2021, the US Department of Energy (DOE) launched the Carbon Negative Shot programme to encourage the development of durable CDR at <$100/t – importantly, the programme also supports MRV development [54]. To support this initiative, the 2022 Bipartisan Infrastructure Law provided billion-dollar investments in the US's carbon capture and CDR industry, with $3.5 billion allocated to DAC research and development [55]. On the demand side, the DOE also announced a $35 million CDR Purchase Pilot Prize in which the US government directly buys removals through a competitive process. Moreover, a proposal for government procurement of CDR to the tune of $2 billion has been introduced in Congress [28], [56]. There are also relevant philanthropic activities ongoing in the US, such as Elon Musk's $100M Carbon Removal XPRIZE.

The United Kingdom. The UK is actively discussing pathways to incorporate CDR into its policies given the legal requirement for the government to achieve net zero by 2050 [57]. CDR deployments are mentioned in the Net Zero Strategy [58]. The most recent strategy brief indicates interest in BECCS, DACCS, biochar and enhanced rock weathering, as well as regulatory oversight for MRV. In 2022, UK Research and Innovation (UKRI) announced £100M for greenhouse gas removal research, development and demonstration across the themes of DAC, enhanced rock weathering, biochar and BECCS [59], [60], [61], [62]. However, the UK's regulatory framework currently only supports land-based CDR for mitigation [63]. The newly established Department for Energy Security and Net Zero are consulting on frameworks for CDR projects based on contracts for differences, as well as potential inclusion of CDR approaches into the UK ETS [64].

The European Union. The European Climate Law has instituted dual targets for emissions reduction and carbon removal to limit mitigation deterrence, with 225 Mt/y carbon dioxide removal expected from land-based CDR approaches [2]. The European Council and Parliament has agreed on an EU-wide certification scheme for CDR aimed to ensure CDR quality and seize the new economic opportunities presented by the new industry [65]. Several projects, such as NEGEM, are funded by Horizon 2020 to improve the quantification of CDR, but overall funding for CDR research and development is low in comparison to what is needed [66]. National funding and the EU Innovation Fund is also available for CDR, for example Sweden has a BECCS project that was co-financed with €180M by the EU Innovation Fund. However, most of these funding is not ringfenced for CDR initiatives, meaning that other carbon management activities can qualify for grants (such as carbon capture and utilisation). CDR start-ups at first-of-a-kind stage (series A/B in venture capital terms) are finding it extremely difficult to get projects and infrastructure financed for a variety of reasons including: lack of government support/funding, founders' lack of familiarity with different forms of debt, and a poor risk appetite from national investment banks and pension fund managers. To fill the gaps in the capital stack, private companies and extremely large philanthropies are beginning to guarantee debts or provide loans and infrastructure investments [67]. For example, Denmark's first BECCS initiative was co-funded by Microsoft.

The EU's response to the IRA was to launch the European Green Deal that was widely criticised for not going far enough to support climate innovation, including CDR. However, the Carbon Border Adjustment Mechanism could present meaningful opportunities for CDR demand. Countries leading European discourse are the Nordic countries, France, UK, Switzerland, and Germany. However, there is little attention being given to CDR in high-income countries within Eastern Europe.

CDR activities outside of North America and Europe

Other high-income countries that are planning or considering CDR include: Australia, Chile, Japan, Oman and South Korea [46]. For example, Australia is considering the integration of CDR into the Carbon Credit Union Scheme [68]. There is a clear need to expand the debate on CDR to regions other than North America and Western Europe – in particular, to countries in the Global South that are often cited as locations that will be promising new hotspots for the CDR industry [69]. Lower-middle income countries that have indicated an interest in incorporating CDR into their long-term plans include: Colombia, India, China, Thailand and Indonesia [46]. Theoretically, if people buy CDR, this new industry could be an opportunity for local growth and development. For example, DAC projects spearheaded by local leaders have been proposed in Kenya, where it is hoped that investments in energy infrastructure and the workforce would make the CDR industry an excellent opportunity for economic growth [70], [71]. However, it is important to bear in mind that initiatives supporting the development of supportive CDR policies in Western countries may find that the same tactics are either less effective or not effective in Latin America or Indonesia because CDR is rarely treated as its own industry outside of the US, UK and EU. CDR policies, therefore, need to fit within other industrial strategies [2].

Why do we need government buy-in?

Governments can support the CDR industry in many ways by incentivising both supply and demand, as well as by upholding quality and justice. For example, by supporting and standardising robust MRV, carbon removal markets can draw from a stronger scientific basis to demonstrate efficacy and safety. The knowledge that there are strong regulatory frameworks governing CDR projects would help build people's trust in this new industry (this is an issue; see Public Attitudes to CDR).

Another important and unique role government can play is to invest in or subsidise the associated shared infrastructure. This infrastructure is so expensive and the technologies so relatively risky that the private sector alone cannot be expected to provide it. Some have proposed classifying CO_2 as a waste product that should be dealt with like any other public waste: collected and removed by public services, funded by taxes of some sort, but fundamentally a government responsibility [72].

Significant Investment Required in Complementary Infrastructure. Many novel CDR approaches are expensive because large amounts of mass and energy are moved, produced and/or consumed to remove CO_2 from the atmosphere, so significant infrastructural investments are required for the novel CDR industry to scale. For example, BECCS moves biomass and produces electricity, DAC consumes electricity and heat, extracts CO_2 from air, and that CO_2 is generally stored in underground reservoirs, sometimes requiring miles of pipeline for transportation. CO_2 itself is classified as a hazardous or dangerous substance in many jurisdictions and is usually transported at high pressure (and/or low temperature) as a liquid or supercritical fluid, which creates additional potential for a major incident (see: Safety Concerns). This infrastructure could be shared with carbon capture technologies but at the moment, very little of it exists and there is a significant first mover disadvantage for start-ups that are ready to scale up to demo or pilot level. In addition, since the major players in CDR are currently pre-commercial or early-stage start-ups (research projects up to series A), they are running on either grant funding or venture capital money, neither of which generally cover infrastructure investments. Large investments are needed for CDR to scale, the likes of which only very large multinational companies can deploy. However, when large multinationals do invest, it can be interpreted as 'greenwashing' and this damages social acceptance of CDR (to be discussed more in the Public Attitudes to CDR section). For this reason, public policy and associated funding could be important to catalyse finance and solve the infrastructure bottleneck pre-competitively. In addition, government investment in research and development is a huge source of training opportunities. Given that access to talent is an issue affecting CDR start-ups, an increased workforce is critical to both carrying out the appropriate pilot tests and demonstrations required, as well as to deploying CDR at scale [22].

A Lack of Fit-for-Purpose Permitting. Permitting or consenting would be required to demonstrate CDR methods and build related industrial and transport infrastructure but since not many terrestrial novel CDR projects (see next paragraph for discussion of mCDR) have undergone permitting yet, it is hard to precisely identify true bottlenecks in the process as they are highly technology- and geography-dependent. For example, there are bespoke requirements for geological storage in many jurisdictions. Closed system CDR will likely face fewer permitting barriers because the risk of harm is less systemic and MRV is simpler, so overall there is more confidence in the safety of the method. However, looking to CO_2 storage and pipelines – infrastructure that is essential for the future – there have been issues when planning and implementing projects due to legal restrictions on (and social resistance to) carbon storage in a number of countries or states [73], [74], [75]. In general, carbon storage is currently proceeding in accordance with multiple and sometimes patchy layers of decades-old national, subnational, and Indigenous laws pertaining to land use, drinking water purity, waste disposal and so on.

Needs for International Legal Frameworks. While most marine CDR activities and research to date have been conducted within national jurisdictions, the mCDR field faces significant barriers because the laws regulating ocean activities do not provide space for CDR research and demonstration. Key international laws applicable to mCDR include the London Convention (LC) and London Protocol (LP), which require parties to adopt domestic laws regulating ocean dumping. However, the parties to the LC and the LP have agreed that certain projects are exempt if they involve legitimate scientific research and mechanisms are in place to prevent, reduce, and manage adverse environmental impacts [76]. These activities are regulated by a precautionary approach, which only allows activities with legitimate scientific research where "no economic interest [is] influencing the design, conduct and/or outcomes" and "no financial and/or economic gain [arises] directly from the experiment or its outcomes" [77]. This could prevent privately backed research that is funded by the sale of carbon credits or through similar mechanisms. If some countries were to allow large-scale research or commercial deployments, they could face pushback from the international community and there could be implications for social license to operate. There is reason to believe that the parties may strictly apply the requirements of the assessment framework and take a narrow view of research. Legal ambiguity is a major hurdle for advancing marine CDR. MRV improvements are required to inform legal contexts that are fit-for-purpose for such open system climate interventions. In practice, the focus of both the LC and LP is on assessing potential risks, which will be difficult to evaluate without proper monitoring tools, field trials and experiments. In the event that political mechanisms do not move fast enough for the field, codes of conduct may be of use, although several exist and gaining buy-in is not straightforward [78], [79].

Public attitudes to CDR

Public support of CDR is crucial for its widespread adoption: it helps to ensure projects have the social licence to operate at the local level, spurs investments, and builds political will for removal policies. There are generally low levels of public awareness of CDR in geographies that have been studied (Western Europe, the US, Australia and New Zealand) [2]. This suggests that other countries that were not studied might have even lower levels of awareness. When people have heard of CDR, it is typically thanks to media coverage, and sometimes confused with industrial carbon capture and storage (CCS) [80]. The main drivers of social opposition are greenwashing concerns, mitigation deterrence, safety concerns, and technical uncertainty resulting from scientific knowledge gaps. If left unaddressed, these narratives risk eroding public and political support.

Figure 4. Selection of news headings showing public scrutiny over CDR projects or investments.

Greenwashing & mitigation deterrence

Much attention was given to Occidental Petroleum's $1.1 billion investment into Carbon Engineering, a DAC company. This move attracted controversy because the Chief Executive of Occidental was quoted saying that CDR "gives our industry a license to continue to operate for the next 60, 70, 80 years" [81]. Sadly, in the US, oil and gas companies get the same 45Q tax credits to use CO_2 for enhanced oil recovery (EOR; a mitigation strategy) as legitimate negative emissions technologies such as DACCS. Indeed, Occidental possesses several oil fields that do not produce oil without enhanced oil recovery [82]. Greenwashing by offsetting reducible emissions is a major concern when it comes to corporate climate action, and the same concern applies to carbon removal where there is a lack of clarity around what constitutes legitimate residual emissions that require CDR, and whether or not carbon removal will be a lifeline for fossil fuel companies to continue polluting. There is a real and present risk of moral hazard (also called mitigation deterrence) that the scale-up of CDR could allow some companies (and perhaps nations) to deter or deprioritise their decarbonisation commitments in the near term because of the potential opportunities to address emissions later [83], [84].

Safety concerns

There are many ways in which CDR methodologies (especially open system CDR) or infrastructure could be dangerous. Many carbon dioxide removal or storage techniques can use industrial wastes or leftover fines from mining activity to mineralise carbon dioxide. It is essentially that these feedstocks are processed and utilised carefully to protect communities from particulate pollution and potential water or soil contamination. With respect to infrastructure, as stated previously, pressurised CO_2 is a safety hazard and requires proper storage, transportation, and handling. Because CO_2 is heavier than most components of air, it can cause suffocation by displacing oxygen. In 2020, a pipeline carrying CO_2 and H_2S for enhanced oil recovery leaked in Mississippi. The nearby town, Satartia, ran out of oxygen so quickly that cars would not start and residents fell unconscious as they tried to escape [85]. Luckily there were no deaths, but the incident has frightened local communities and made them hostile to the new infrastructure that the CDR industry may need at scale. In response to this incident, several state and local governments adopted laws to restrict CO_2 transport and storage – a clear example of how public acceptance drives the development of policies and vice versa.

Technical uncertainty

Some see novel CDR approaches such as DAC as a deus ex machina – a magical remedy for historical wrongs that is unlikely to work in reality [86], [87]. As alluded to earlier (refer to: Significant Investment Required in Complementary Infrastructure), most types of CDR are resource-intensive – whether this might be land use, electricity, water or mineral requirements. Not all forms of CDR should or will scale. For instance, scaling up DAC is problematic if there is not enough renewable electricity available, increasing ocean alkalinity does not always lead to net atmospheric CO_2 removal, and there are gaping knowledge gaps with respect to second order impacts of certain CDR techniques more generally [88], [89]. Conversely, there may be techniques that benefit from economies of scale or whose full efficacy can only be determined by undertaking a critical number of field trials (especially true in marine contexts). However, technical uncertainty mixed with CDR companies performing their own MRV risks undermining public trust and derailing CDR projects, as was clearly demonstrated by the social opposition to mCDR company Planetary Technologies' mesocosm studies in Cornwall [37].

Confusion between different types of CDR in the market system

A World Economic Forum report published in 2023 showed that most CDR buyers do not perceive the differences between traditional emissions reduction offsets, nature-based CDR, and novel CDR credits. Indeed, only 27% of respondents understood the dissimilarities [90]. This creates several issues. First, the lack of clear differentiation between these pathways poses a challenge for start-ups in the novel CDR space when trying to distinguish their credits to potential corporate buyers. Second, the existing (voluntary) market system is complex and fraught with different standards and misaligned incentives that transcend CDR [91]. As a result, and since all projects are competing for buyers, there has been a tendency towards a destructive narrative that one type of CDR is more scientifically proven, commercially relevant (and so on) which has further contributed to public scepticism towards CDR projects.

Challenges in science communication and public engagement

Public awareness and proactive stakeholder engagement are critical to prepare communities for the birth of a new industry. There are examples of where this has been done really well, such as Project Bison in Wyoming [92]. However, most community engagement has been carried out in a reactionary way, for the purpose of achieving social license to operate once the stakeholders have already galvanised against a project [93]. Public support is crucial for the success of the CDR projects; research shows that only 13% of renewable energy projects that have faced public opposition are completed [94]. Initiatives that successfully achieve community buy-in could have an outsized impact by removing a barrier for the deployment of CDR, but what 'good' engagement looks like is, as yet, unclear. Social scientists and practitioners are drawing from experience gained from other clean tech projects, but there is no evidence to suggest that, given all the information, people will support CDR projects. The XPRIZE is tackling this problem by mandating communications training for entrants to their carbon removal prize [95].

An element of this challenge is how benefits and risks are understood and conveyed to stakeholders. To date, there are no coordinated efforts to arm journalists with accurate information and resources to build narratives. Conflations between carbon removal and carbon capture are common, as are failures to distinguish between good and bad CDR practices. Strategic communications that can familiarise stakeholders with the risks and benefits of CDR, as well as the risk of inaction and the co-benefits that may be realised, are sorely needed. A great deal of nuance and sensitivity will be required within those communications and engagement, but if there are diverse local voices coalescing into a cohesive global narrative, this could be a catalytic lever to help CDR scale. The counterfactual is that opposition to one particular project or approach could influence a wider narrative that threatens the viability of the entire CDR industry.

Conclusions

As an industry, CDR faces a suite of bottlenecks to scale, including the need for more research and development to de-risk various CDR approaches, access to financing, resources, and talent. In many cases, new regulatory frameworks are necessary. These challenges are especially pronounced given that there is no organic demand for CDR, and that many people are still uninformed of its possibilities and benefits. Therefore, a supportive socioeconomic and political environment is required to scale the CDR industry at pace. Non-governmental support is important for CDR because action is needed quickly. However, **it is critical that governments right-size and invest in CDR now** so that a portfolio of approaches is at our disposal to address climate change. Care must be taken to stick to the facts: removals are not a panacea, and incentives for CDR must not supersede those aimed at emission reductions.

A key intervention is to **drive demand for a portfolio of CDR approaches**, beyond what is happening on the VCM. Effective policy is required to stimulate demand, which should have trickle-down effects including an increase in research, development, and demonstration funding, resources, and other enabling factors to prepare the CDR industry for scale. Supply of high-integrity, durable CDR should also increase in response to strong demand signals. Policy can help to create useful frameworks and direct investment toward research, development, and demonstration to improve the efficacy and safety of CDR projects. These activities also help to drive the creation of a new workforce for the industry.

In order to direct public resources towards CDR, **additional scientific research and development activity is required**. The needs for research and demonstration funding are highly pathway-dependent (see RMI's Applied Innovation Roadmap for CDR). In general, it is mission-critical to reduce or define the scientific uncertainties in CDR pathways that rely on nature, such as marine CDR, enhanced rock weathering, geological carbon mineralisation and soil carbon sequestration. Paying more attention to the scientific foundations of CDR would also support the development of MRV, so investing in research and development could increase stakeholders' confidence in the value of CDR projects. In turn, this could drive more demand for CDR. In addition, the generation of baselines and MRV solutions will support governmental regulation of the CDR industry. Without this, regulations, standards, and directives will remain to not be informed by robust science. This is particularly important for open-system CDR, where foundational science and MRV research can be extremely expensive and receives significantly less support from other stakeholders. Uncertainty around what to measure, as well as when and how, will delay commercial CDR activities and erode public trust. Hence, it is necessary for governments to step in and break this cycle with funding, policy, and regulation.

Work is needed now to ensure that policymakers are equipped with the tools and education to enact policies for CDR. This should include social sciences research with a focus on first-mover geographies.

Advocacy should focus on:

i. creating demand for CDR, and;

ii. establishing an enabling environment via regulation of the market and projects.

Also, governments need to engage with communities and position CDR as a public service, thereby justifying significant public investment into demonstrations. These demonstrations can help to show local communities that CDR benefits them. Rapid scale-ups should not be pursued without due consideration of the current social concerns around the industry. There is an opportunity to gain public buy-in for CDR by leveraging strategic, two-way communications that encourage the design of fairer and more inclusive CDR approaches.

In conclusion, political advocacy in targeted geographies to:

i. guarantee demand;

ii. increase supply of high-integrity CDR (this includes providing funding for research, development, and demonstration projects), and;

iii. create relevant frameworks is a high-leverage way to scale the CDR industry.

MRV is also a highly cross-cutting way to increase the legitimacy and demand for CDR in the short term whilst providing the evidence base for political advocacy.

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