https://doi.org/10.1038/s43017-023-00493-y

Controversies of carbon dioxide removal

Kevin Anderson, Holly Jean Buck, Lili Fuhr, Oliver Geden, Glen P. Peters & Eve Tamme

Check for updates

Various methods of carbon dioxide removal (CDR) are being pursued in response to the climate crisis, but they are mostly not proven at scale. Climate experts are divided over whether CDR is a necessary requirement or a dangerous distraction from limiting emissions. In this Viewpoint, six experts offer their views on the CDR debate.

Carbon dioxide removal (CDR) encompasses various deliberate human approaches that can remove CO_2 from the atmosphere and store it in oceanic, terrestrial or geological reservoirs over climate-relevant timescales of decades to millennia. These approaches include schemes such as reforestation, afforestation, iron fertilisation, ocean alkalinity enhancement, enhanced rock weathering, bioenergy with carbon capture and storage (BECCS) and direct air capture and storage (DACCS). CDR is distinct from methods aimed at preventing new emissions at point sources, such as carbon capture and storage (CCS) at fossil power plants or cement works, as these prevention methods are classed as emission reduction strategies.

Why are climate scientists divided about CDR?

Eve Tamme: The Intergovernmental Panel on Climate Change (IPCC)[1] has established CDR as an essential and unavoidable tool to achieve net-zero greenhouse gas (GHG) emissions. However, scientists' views differ regarding the expectations for the required annual volumes of CDR by 2050, with the lower end around 1.5–3 billion tonnes (ref. 2) and the higher estimates stretching from 4.7 to 10 billion tonnes per year[3]. Ultimately, the amount of CDR needed depends on how swiftly global emissions can be reduced, the level of residual emissions and how these residual emissions will be restricted over time.

Economists and physical scientists tend to focus on different aspects regarding CDR. Economists are looking at it as a climate change mitigation solution that offers certain volumes and price ranges, especially in the context of carbon pricing mechanisms. Physical scientists focus more intensely on the actual climate impact, the questions around the durability of different CDR methods and how to bring these aspects together. Transferring the expertise from the physical scientists to the realm of economists will help design policy tools, including carbon markets, that deliver real climate benefits.

Glen Peters: There are two broad areas of disagreement on CDR, revolving around the technical feasibility at scale and how CDR is used in mitigation discourse.

CDR started appearing in mainstream emission scenarios in the late 2000s (ref. 4) and has become a dominant element of most mitigation scenarios consistent with the Paris Agreement's temperature goals. Initially, CDR was dependent on the assumed success of CCS applied to bioenergy (termed BECCS). Although there was much promise for CCS in the 2000s, including an IPCC Special Report in 2005, the technology has not yet lived up to its hope, despite lofty policy ambitions[5]. CCS and most CDR methods are a complex set of technologies that have proved difficult to deploy at scale in real-world contexts. The repeated failure of CCS and CDR to deliver as promised has led many to question their feasibility, particularly at scale.

In addition, CDR has long been identified as a potential 'dangerous distraction'[6] owing to its widespread deployment in emission scenarios but not in reality. Given that the entire mitigation agenda is predicated on CDR working at scale, and if CDR does not work at the scale intended, then the world will go more rapidly into carbon debt and be locked into a higher-temperature pathway[7]. A more risk-averse approach that uses only a modest scale of CDR would require greater near-term emission reductions that avoid going into carbon debt[7]. If real-world rate and scale constraints keep CDR marginal, it can never compensate for a failure to sufficiently reduce emissions. Hence, the best antidote to a risky temperature overshoot is to reduce emissions, even if CDR shows promise.

Oliver Geden: There are good reasons to be cautious about the promise of large-scale future CDR deployment. This caution can revolve around negative side effects when implementing methods like BECCS and afforestation, for example, when it comes to competition with land suitable for food production, especially in the Global South. Additionally, there is a problem when enormous volumes of CDR are built into implausible mitigation scenarios for the second half of the century, generating a false sense of optimism that we can still meet ambitious temperature goals, even though global emissions are still not declining. I got into the CDR debate prior to the Paris Agreement in late 2015, by criticizing the use of CDR in scenarios for effectively masking insufficient political action while not making policymakers aware about the important role that future CDR deployment already played in IPCC Annual Report 5 (ref. 8).

With the advent of the global 1.5 °C goal and net-zero emission targets, and with more and more scientists arguing that CDR is needed to achieve these targets, the debate slowly started to shift towards a serious discussion around which CDR methods should be deployed by whom, by when, at which volumes and in which ways – and recognizing that we are already doing CDR, mostly in the form of conventional land-based practices like afforestation and reforestation[9].

Holly Jean Buck: CDR has some role in responding to climate change and reaching net-zero emission targets. However, there is a range of opinions about what approaches deserve further research and what amount of CDR is realistically possible versus what is desirable.

Viewpoints on the desirability, type and amount of CDR depend on one's assumptions about how fast technological development and social change can happen. For example, if you are from a social group that believes a rapid global phase-out of fossil fuels is possible, and are optimistic about the possibility of the development of renewables, green hydrogen and other mitigation technologies but not optimistic about carbon management technologies, you might not see a need for much CDR. If the political belief of your social group is that it is possible and desirable to dramatically reduce the demand for fossil energy in the global North, then you might not see a need for much CDR. If your belief is that it will take more time to develop mitigation strategies for the hardest-to-abate sectors, you might think society should invest in CDR. Climate scientists are going to be divided on their beliefs and views about how the world works, just like any other social group.

Science can bound the numbers of what is technically feasible with regard to CDR versus emission reductions, and can tell us some important things about trade-offs in terms of land, water or energy between different options — but science cannot be the sole authority on what pathway society should take towards net-zero emissions.

Kevin Anderson: I see the division regarding CDR arising primarily from the pressured working lives of academics, a failure to take the time to carefully consider each other's respective arguments and an increasing societal preference for polarized positions. When having conversations privately over a coffee or a pint or via an open-ended virtual discussion, many of the disagreements between climate scientists rapidly resolve into issues of scale and timeline rather than the science of CDR itself.

These more nuanced positions then escalate into apparent disagreements when Integrated Assessment Models (IAMs) are used to develop mitigation scenarios to deliver on the Paris Agreement's 1.5–2 °C commitments. The main (IAM) modelling groups might work quite objectively, but they do so within deeply subjective political boundaries[7]. Their low carbon futures are locked into tech-dominated versions of the present with no changes to core political elements or values of society in relation to fairness, or distribution of resources or power. Such tight political criteria, combined with very small carbon budgets, force all mitigation scenarios assessed by the IPCC to include increasingly extreme levels of CDR.

As such, although typically there is private agreement between climate researchers that the levels of CDR required are extreme, to express such concern in public raises challenging political questions, an area where most scientists simply fear to tread. Ultimately, CDR in the models both sidesteps overt political choices and locks in today's political norms. In relation to energy emissions aligned with the Paris Agreement, CDR is much more an expedient political football than a serious technical consideration.

Lili Fuhr: Amongst scientists and activists, there is a consensus that we need to go beyond reducing emissions and that the most effective strategy is to phase out all fossil fuels as fast as possible[10]. That also means that any measures taken to mitigate climate change must not slow down or divert political attention and funding away from that main strategy. When it comes to CDR, the terminology can be confusing as it combines two very different methods: restoring natural carbon sinks, such as forests, soils or oceans, and investing in unproven technologies, like BECCS, DACCS or enhanced weathering. We absolutely need to protect and restore natural carbon sinks to enhance their capacity for biological carbon sequestration. Restoration of natural carbon sinks should certainly not be used to justify any additional industrial or fossil fuel emissions[11]. Speculative and largely unavailable CDR technologies are very different because they would require setting up entirely new industrial infrastructures at a large scale. As such, the majority of groups in the global climate movement see them as false solutions and dangerous distractions[12].

How essential are CDR approaches to meeting climate targets and combatting climate change?

GP: The IPCC essentially outlines three potential and distinct phases of CDR in the mitigation portfolio.

In the first phase, before net-zero emissions are reached, CDR helps reduce net emissions, but its role is marginal in comparison to the role of emission reductions. Gross CO_2 emissions (excluding removals) decline in excess of 80% from today until net-zero CO_2 emissions in the average scenario, with CDR scaling from close to zero today to fill the remaining 20% gap.

In the second phase, CDR is necessary at the point of net-zero emissions (CO_2 or GHG) to counterbalance the so-called hard-to-abate residual emissions. These are the emissions that remain after all emission reduction options are exhausted, including political or social barriers. However, the definition of 'hard-to-abate' is obviously a slippery slope.

In the third phase, CDR is used to achieve net negative CO_2 emissions by removing more CO_2 from the atmosphere than is emitted. These net negative emissions are expected to lower the global average temperature, after exceeding a temperature target ('overshoot'). In this CDR scenario, a climate target is knowingly, perhaps deliberately, exceeded on the assumption that the climate problem can be cleaned up by future generations with a costly technology with limited evidence that it will work at scale[7].

OG: Essentially, stopping global temperature rise requires some level of CDR because stabilization can only be achieved with net-zero CO_2 emissions, in which the 'net' indicates the assumption that there will be residual CO_2 emissions left at the time of net zero, to be counterbalanced by CDR[13]. And because the IPCC AR6 Synthesis Report made it clear that the warming level of 1.5 °C will be reached and probably crossed in the 2030s, the world would even need to go one step further and try to achieve net-negative CO_2 emissions globally in order to attempt to bring temperature down to 1.5 °C again[13].

The contributors

Kevin Anderson is a professor of Energy and Climate Change. Previously he held the Zennström professorship (Uppsala, Sweden) and was director of the Tyndall Centre (Manchester, UK). Kevin engages with governments, industry and civil society, has a decade of experience in the petrochemical industry, is a chartered engineer and is a fellow of the Institution of Mechanical Engineers.

Holly Jean Buck is an Assistant Professor of Environment and Sustainability at the University at Buffalo, and her research focuses on public engagement with emerging climate technologies. She is the author of the books *After Geoengineering* and *Ending Fossil Fuels: Why Net Zero Is Not Enough*.

Lili Fuhr directs the Fossil Economy Program at the Center for International Environmental Law. She has followed the IPCC's 6th Assessment Cycle as an expert reviewer for the Special Report on Global Warming of 1.5 °C and participated as an observer in the Synthesis Report approval plenary. Lili sits on the Steering Committee for the Fossil Fuel Non-Proliferation Treaty Initiative.

Oliver Geden is senior fellow and head of the Research Cluster Climate Policy and Politics at the German Institute for International and Security Affairs (SWP). He is co-editor of the annual State of Carbon Dioxide Removal report, acted as lead author for IPCC Sixth Assessment Report (AR) Working Group III and the Synthesis Report, and is currently vice-chair of IPCC Working Group III.

Glen P. Peters is a senior researcher at CICERO Center for International Climate Research who explores trends in global carbon dioxide emissions and how they link to future emission pathways and global climate objectives. He is on the executive team of the Global Carbon Budget and was a lead author for the IPCC Sixth Assessment Report on emission scenarios.

Eve Tamme leads Climate Principles, a climate policy advisory. She has worked on climate policy since 2004 in public and private sectors, specializing in European and international policy developments. Her work focuses on carbon removal, carbon markets, carbon capture and climate governance.

There could have been times when mitigating less in the near-term and making up for it with net-negative CO_2 emissions in the far-away future was mainly a result of macroeconomic optimization in scenarios[8], but with a rapidly depleting carbon budget for 1.5 °C, there is no credible pathway left without going net-negative emissions. However, this net-negative scenario could be unfeasible, and to make it more likely to be feasible, the cumulative CDR volumes need to be kept in check, which again is an argument for prioritizing emission reductions[3].

HJB: The IPCC states that "CDR is a necessary element to achieve net zero CO_2 and GHG emissions both globally and nationally, counterbalancing residual emissions from hard-to-transition sectors. It is a key element in scenarios that limit warming to 2 °C (>67%) or lower by 2100 (*robust evidence*, *high agreement*)."[9]. Even low energy demand scenarios still require some amount of CDR[14], although they can bring this number lower by ramping up things like energy efficiency or making assumptions about what amounts of living space or meat consumption can be allocated per person. Clearly, some CDR capacity is essential for reaching net-zero emission targets. There is already about 2 billion tonnes of CDR occurring on land[3], but there is the question of how much that can be maintained and enhanced under climate change.

LF: Climate targets are set by governments, not scientists. But the science presented by the IPCC has left no doubt that irreversible impacts would come from overshooting 1.5 °C, that there are huge physical uncertainties of doing large-scale carbon removal, that reliance on future CDR is delaying deep emission cuts now[15] and that CDR technologies like BECCS and DACCS come with potential risks and harms for ecosystems and communities.

As the fossil economy is threatened by the economic viability and competitiveness of renewable energies, big polluters and fossil fuel companies are promoting technological CDR as a cover-up for expanding their business. This cover-up is clearly not aligned with IPCC findings. The IPCC's Working Group III report[1] highlights the dangers of overreliance of governments on these unproven technologies. Unfortunately, these warnings are downplayed in the heavily negotiated IPCC Summary for Policymakers. They are buried under an array of models and pathways that rely on precisely such technologies, that project continued use of fossil fuels for decades and that overwhelmingly assume that the world will go beyond 1.5 °C for decades or longer — with surprisingly little attention paid to the human and environmental consequences such assumptions entail.

KA: The ubiquitous assumption of planetary-scale CDR has been a key factor in derailing the 2015 Paris Agreement 1.5 and 2 °C commitments as well as the obligation to "avoid dangerous anthropogenic interference with climate system" enshrined in the original United Nations Framework Convention on Climate Change in 1992. Absolutely central here is the distinction between CDR itself and the ubiquitous assumption of planetary-scale CDR in the IAM models. In so many respects, the major IAM modelling groups have inadvertently done the bidding of both Big Oil and those deeply wedded to the obscene asymmetry in responsibility for emissions[16]. Since the early 2000s, these models have increasingly normalized many hundreds of billions of tonnes of CDR as a means of maintaining the political status quo and seriously delaying the need to phase out fossil fuels.

It is now October 2023, and even the most optimistic reading of the science suggests we have around 8 years of current emissions before we exceed the carbon budget for a 50% chance of not exceeding 1.5 °C, having squandered almost 0.3 trillion tonnes of CO_2 since the Paris Agreement in 2015. In an emergent process of appeasement, an alliance has arisen between failed (and failing) political leadership and complicit IAM modelling of the community's escalating dependence on CDR to reconcile the irreconcilable of delivering on the Paris Agreement 1.5 °C to 2 °C commitments without rocking the political boat. As such, from an energy-only perspective, I have long viewed CDR as a dangerous distraction from timely zero-fossil-fuel narratives.

ET: The Paris Agreement requires "balancing emissions by sources and removals by sinks in the second half of the century". First and foremost, getting to that stage requires very steep emission cuts in the next couple of decades. The more successful the world is in rapid decarbonisation, the less CDR will be needed during the net-zero point, and for net-negative emissions thereafter.

When putting this reality in the context of the question at hand — how essential is CDR — the clear answer is that reducing emissions is the most urgent task today. There is a role for CDR deployment next to it, but it is not the main priority when looking at the big picture.

Zooming in on CDR in its complementary role next to emission reductions opens up a vast ecosystem of CDR methods. Given that all these methods have limitations, a growing portfolio of CDR approaches needs to be developed and deployed simultaneously to have the best chance of removing the required volumes of CO_2 by mid-century and beyond.

Which CDR methods do you think could be promising?

LF: Promising for whom? Delaying deep emission cuts into the far-away future is a convenient way for big polluters to distract from the urgency to start phasing out fossil fuels today and to drastically reduce emissions in the critical decade ahead. The oceans, forests and soils are the best allies we have in removing excess carbon from the atmosphere. But as the climate is heating up, extreme weather events are becoming more frequent and we are approaching various tipping points; we risk losing the sink capacity of various ecosystems. The fossil fuel industry is also polluting them with microplastics and toxic chemicals, which further threatens their survival and carbon storage capacity.

The way in which we produce food and manage land can have a key role in storing carbon in soils. Indigenous peoples have acted as stewards of these ecosystems for hundreds of years. Protecting their rights is in the interest of everyone. Industrial-scale 'carbon farming' to produce carbon credits is a false and dangerous promise.

GP: If we look at solar, wind, electric cars or batteries, we have direct evidence of what looks promising, through operation and deployment. It is not possible to say which CDR methods are most promising because, so far, all have failed to deploy at any meaningful scale. It is possible to postulate theoretical pros and cons of each CDR method, but without sufficient deployment, they remain theoretical. Even afforestation and reforestation have limits, not only in terms of land competition but also in resilience to a changing climate and verifying how much carbon dioxide is removed over extended periods.

KA: For the purposes of this conversation, I will focus on two forms of technology-based CDR, BECCS and DACCS, and one so-called nature-based solution.

As an engineer with a background in design and construction in the petrochemical industry, I feel a streak of professional shame when, in 2023, the pinnacle of engineering prowess is burning plants and burying the carbon (termed BECCS). There are many reasons for this shame, but key amongst these is the very low energy density of plants. Add this to the inefficiencies in thermal electricity generation and nation-sized areas of land needed to be put aside to deliver the volumes of BECCS assumed in the IAM models. Yet, with very few exceptions, it is such an unsustainable and yesteryear approach to current problems that the IAM modelling groups evoke on a huge planetary scale. So, for me, and on so many levels, BECCS is a blunder of monumental proportions and illustrates just how low we are prepared to stoop to get the carbon molecules to add up in models.

DACCS is a much more elegant engineering option than BECCS. DACCS typically relies on renewable energy to flow air over a catalyst, where the CO_2 is captured before being stripped from the catalyst and subsequently stored. Despite its engineering appeal, it is still a fledgling technology and with very little scope to deliver real carbon reductions within the tight 1.5 °C–2 °C timelines. Moreover, as it stands today, in almost all nations, electricity, the key power source for DACCS, is under 20% of 'final energy consumption', and only a relatively small fraction of that is from low carbon generation. A triage approach to how we use what low-carbon energy supply we have would very likely see DACCS a long way down the priority order.

In terms of nature-based solutions, planting trees is the most widely discussed approach. However, the carbon budgets provided by the IPCC already rely on a massive shift away from deforestation and a programme of forestry management, reforestation and some afforestation. So caution needs to be applied to ensure these options are not double counted. Moreover, as we are increasingly witnessing, trees are not a secure carbon sink, as situations such as fire, land use practices, fuel shortages or pest movements can release the carbon back into the atmosphere. Finally, whilst there is immediate popular appeal to planting trees as a store of carbon, in practice, trees need to be considered as part of a rich ecosystem, including their impact on soil carbon cycling.

In my view, BECCS has little to no worthwhile potential, for multiple reasons. DACCS and some carefully applied nature-based solutions could have a useful role in GHG mitigation but should in no way be assumed to compensate for any fossil fuel emissions.

OG: The most promising CDR methods will strongly depend on regional geographical and climatic conditions and how political preferences or social acceptance evolve in different countries. Although there should be specific attention to potential co-benefits and synergies with other societal goals like socioeconomic development or biodiversity, it is important to keep a strong focus on CDR methods with characteristic timescales of storage beyond 100 years, like biochar, enhanced mineral weathering or DACCS.

ET: CDR methods range widely regarding their climate mitigation potential, technology readiness level (TRL) and expected price range. Conventional CDR methods like afforestation, reforestation, soil carbon sequestration and peatland restoration have the highest TRL levels but do not offer long-term durability for CO_2 storage. DACCS, BECCS and biochar are much more novel methods that offer strong mitigation potential and high durability and are not too far behind in terms of TRL. It is essential to support the scale-up of technologies that are ready to be commercialized, whilst helping newer promising CDR methods to continue innovating and moving to higher technological readiness levels.

HJB: Biomass carbon removal and storage involves using biomass (such as algae, municipal waste, agricultural or forest residues) to remove CO_2 from the atmosphere and store it underground or in products. It looks promising in many areas but is very context-dependent. There are a number of methods that deserve more research, including ocean alkalinity enhancement, enhanced rock weathering and agrigenomic ideas such as engineering plants for enhanced carbon sequestration or microbe-based carbon capture soil amendments. It is early to assess the scalability of all these approaches, and much of the scalability depends on culture and policy. The IPCC assesses that moderate-to-large future mitigation potentials are estimated for direct air carbon capture and sequestration, enhanced weathering and ocean-based CDR methods, with medium evidence and medium agreement[9].

In your view, what are the main socioeconomic problems with CDR?

HJB: The main socioeconomic problem with CDR is that only a tiny fraction of the population is aware of carbon removal, which limits meaningful engagement and just deployment. This lack of awareness is set within the wider problem that many in society do not realize the scope of transformation needed for decarbonization, in terms of deploying clean energy at a massive scale, building electrification, redesigning transport, retrofitting factories, reforming agricultural practices and more. Without that knowledge base, publics are not well-equipped to debate the nuances of CDR approaches within the wider climate response. So if you ask someone whether they want a CDR facility near them, the answer is probably no because it is an unfamiliar industrial project. This is similar to challenges with battery manufacturing plants, transmission lines or other industrial underpinnings of this transition. If you ask people whether they think there should be CDR facilities to compensate for emissions from aviation, or alternatively whether they think there should be limitations on flying, or whether we should use biomass-derived aviation fuels (even if they bring land use and food price impacts) or whether we should carry on as we are despite climate change, who knows what the answer would be. But we are very far from a society-wide deliberation on these trade-offs because the basic contours of the challenge are not fully appreciated.

OG: The main problem is that international policymakers are implicitly relying on remarkably high volumes of CDR to help fix trajectories that already indicate a 1.5 °C overshoot, without necessarily knowing much about CDR or taking responsibility for the expected overshoot. Incorporating CDR in global scenarios is not slowing down emission reduction efforts, but it is hiding the impact of increasing global emissions[17] and sparing climate policymakers the embarrassment of admitting that always staying under 1.5 °C is no longer achievable. But with the advent of national net-zero emission targets, the level of political scrutiny becomes higher, and it is easier to keep expectations about future national CDR levels in check — at least in countries that take their net-zero emission targets seriously[13]. Once governments start splitting their net-zero emission targets into emission reductions and carbon removal components, we can expect healthy national debates on the assumed trajectories, not only regarding CDR but also regarding the types and volumes of residual emissions.

ET: Scaling up CDR could delay reducing emissions. Policymakers can address this risk by establishing separate climate targets for emission reductions and CDR. Given how deep the emission reductions need to be, separate targets help prioritize reductions over removals in the coming decades while also incentivizing CDR to scale it up to the required levels by the right time. A notable example is the design of the European Union's 2030 climate target of a 55% reduction in net greenhouse gas emissions by 2030 compared with those during 1990, complemented by a separate net CDR target of 310 million tonnes by 2030 from the land use, land use change and forestry sector. The contribution of the CDR target towards the 55% emission reduction target is limited to 225 million tonnes. However, the construction of these EU targets and the scope of CDR could be further improved — something the upcoming 2040 climate target proposal is well-placed to address.

CDR must be deployed in an inclusive and considerate way from local to global level. Project developers should meaningfully include local communities in the decision-making process. Environmental justice also has a global aspect, for example, the geopolitical considerations on who is responsible for cleaning up CO_2 from the atmosphere. Developing countries should benefit from the technology transfer of novel CDR methods and have the capacity to decide what is in their best interest and fair contribution when scaling up CDR globally.

GP: Although many advocate CDR for the right reasons, it is important to acknowledge that CDR deters emission reduction efforts[18]. The level of deterrence is difficult to define and quantify. The mitigation levels reported by the IPCC, and used by countries to support their emission pledges, assume that large-scale CDR will be deployed. If the IPCC reduced the reliance on CDR in emission scenarios, the IPCC would report greater short-term net emission reductions, and mitigation policy would have to be recalibrated to a different mix of mitigation measures. The mere existence of CDR in scenarios effectively delays emission reductions, a characteristic not existing for technologies that reduce emissions (such as solar power).

Through time, it is possible to connect various statements and actions of politicians, companies or individuals who claim to be striving toward 'net zero', while continuing or expanding emitting activities and either implicitly or explicitly relying on CDR. This contrasts with emission scenarios, in which all emitting activities rapidly decline and CDR counterbalances small remaining residual emissions.

LF: Both land-based and engineered CDR directly and indirectly threaten human rights, for example those of communities living in or dependent on the land or forests in the areas where a CDR-related activity is taking place[19]. They also indirectly impact human rights by diverting resources from proven mitigation measures and delaying the necessary fossil fuel phaseout. Human rights experts and bodies such as the Advisory Committee to the Human Rights Council, the Special Rapporteur on Toxics and the UN Committee on the Rights of the Child have warned against reliance on unproven, speculative technologies and declared geoengineering — including CDR, marine and solar geoengineering — incompatible with human rights.

KA: My headline view on CDR (and one I have held and made repeatedly over many years) is that we should fund research and development into CDR and deploy such approaches provided they meet stringent social and ecological sustainability criteria. However, we should cut emissions from our energy system assuming CDR will not work at scale. Even if CDR turns out to be as successful as some suggest, it will be required to compensate for the warming from those GHGs that are impossible to eliminate from agriculture, such as methane and nitrous oxide[20].

What are the main technical limitations of CDR?

OG: The technical limitations of CDR depend strongly on the characteristics of CDR methods and respective implementation options, which vary widely in terms of their maturity, removal process, timescale of storage, storage medium, mitigation potential, costs, and co-benefits and risks, and governance requirements[9]. For novel, currently not widely deployed CDR methods like enhanced mineral weathering, biochar or DACCS, the technical challenges widely differ, whereas the sociotechnical challenge is a similar one — passing through a formative phase in which dedicated resources are scarce, risk of failure for individual implementation options is high and adoption is limited to small niche markets. Substantially scaling these novel CDR technologies will require dedicated innovation policies[3].

ET: All CDR methods have distinct limitations. These differ from one method to another and include competition for land or water, reversal of CDR via wildfires, high energy requirements and many other constraints. Access to sustainable biomass, renewables, land and suitable geological formations, among other aspects, define where specific CDR methods are feasible to deploy.

Establishing the exact climate impact of some CDR methods — monitoring, reporting and verifying how many tonnes of CO_2 are removed — has high uncertainty levels, and bringing those down will take time and effort.

Another challenge relates to the durability of different CDR methods, ranging from a few decades to thousands of years. From a climate impact standpoint, it is crucial to guarantee that any residual emissions of fossil carbon are balanced by storage on the same millennial timescale[3]. Shorter durability would only partially balance such emissions. Translating this 'like for like' approach into policy tools is widely discussed in the discourse of incorporating removals into carbon markets[21].

Setting up biochar production is relatively fast, hence, the reason biochar carbon removal has become the leading novel CDR method to deliver tonnes of carbon removed today. Building DACCS and BECCS plants is a longer and more complex undertaking that takes several years. Therefore, very different policy mixes and sequences must emerge to scale the vast ecosystem of CDR methods.

HJB: For direct air capture, low-carbon energy and cost are the main limitations. For biomass with carbon removal and storage, biomass and land are limitations. Other techniques face limitations in terms of land or in terms of robust schemes for monitoring and verification. The most relevant limitations will probably be social rather than technological, given the limited awareness of CDR, the poor conditions of our media ecosystem and the erosion of democracy in many parts of the world.

KA: Firstly, the timeline of staying within carbon budgets aligned with the Paris Agreement's 1.5–2 °C commitments; these are a far cry from the dangerously misleading and highly inequitable net-zero framing that has come to dominate the mitigation agenda. Secondly, there is the naive assumption that a few pilot schemes with chequered technical histories can unproblematically be rolled out at a planetary scale; such adolescent and ubiquitous modelling is far removed from real-world engineering.

LF: Beyond the fact that these technologies are largely speculative and must be weighed against the fundamental uncertainties of removing large amounts of carbon from the atmosphere, I want to highlight one specific limitation: many CDR approaches rely on carbon capture and storage as an enabling technology. The IPCC AR6 Synthesis Report highlights that the implementation of CCS faces technological, economic, institutional, ecological-environmental and sociocultural barriers. It also points out that global rates of CCS deployment are far below those in modelled pathways. These findings are confirmed by real-world evidence: most existing CCS projects in the world are enhanced oil recovery projects. That means that the captured carbon is used to produce more oil, not to reduce emissions. CCS has a decades-long history of overpromising and under-delivering. Despite having been around for decades, CCS facilities currently capture less than 0.1% of global emissions. CDR technologies are not going to be available at scale in the critical decade ahead. A rapid fossil fuel phaseout and rollout of renewable energies alongside energy efficiency and demand-side measures remain the clearest and most certain path to avoid overshoot.

GP: Although CDR works fine theoretically, various technical barriers limit its deployment. I would argue that it is the technical barriers that lead to the standard response that CDR needs greater policy and financial support. CCS is a good analogy. CCS has been around for decades in various configurations, but it has never taken off as a technology. There is debate over whether this is because of lack of policy support or because the technology is not delivering as promised.

CCS and CDR have renewed policy and financial interest; although some full-scale CCS facilities exist, most CDR applications are small-scale pilots or demonstrations. It might be that the CCS and CDR industries have finally overcome the limitations and they will start to scale in the next few years. Time will tell. However, the point remains that almost all emission reduction options are easier and cheaper than CDR, and it is unlikely a company serious about mitigation would rationally opt for CDR over emission reductions. The cost of CDR is also a motivation for engineers to discover cheaper ways to reduce emissions, rather than continuing to emit carbon dioxide only to remove it later with great difficultly and high cost.

What do you recommend is the best way to move forward in the debate and combat climate change?

KA: With specific reference to the role of academics and wider 'independent' experts, and without intending to come across as flippant, I suggest we need integrity, cogency, courage, openness, humility and system-level consistency — all aligned with our United Nations Framework Convention on Climate Change commitment to avoid 'dangerous' levels of climate change or, in modern parlance, not exceeding 1.5 °C of warming (or as near as is possible). Accompanying this, I suggest that it is important that we have complete disinterest in the sensibilities of paymasters, such as the media. In other words, we need to do our work carefully and diligently and communicate our conclusions widely and without fear or favour.

LF: The most ambitious mitigation pathways put out by the IPCC set the floor, not the ceiling, for necessary climate action. Deep, immediate and sustained emission reductions through a rapid and equitable fossil fuel phaseout is the surest path to limiting global warming to 1.5 °C. CDR technologies only serve the interests of big polluters and are a dangerous distraction from what needs to happen.

HJB: Mitigation hinges on having actual climate policy that puts a price on carbon and restricts carbon pollution. Carbon capture and storage has experienced delays for many reasons, but a main one is economic: pollution has had no cost to date, so many big emitters ask themselves what the point is in them installing expensive CCS to reduce their emissions. If we successfully create the conditions for rapid mitigation, we also create the conditions for some amount of CCS and CDR. Until then, the main focus should be on supporting innovation so that when serious climate policy arises, the technology will be ready to deploy. Spending a few billion dollars on the science does not present a serious risk to mitigation. The main mitigation deterrence risk is not from CDR, which few policymakers even know about, but from the fact that fossil fuels are entwined with governments and their stability across the globe. That should be our focus. If we do not get serious climate policy soon, we have bigger problems than debating how to best deal with the last 10% of emissions.

Kevin Anderson[1,2,3] ✉, **Holly Jean Buck**[4] ✉, **Lili Fuhr**[5] ✉, **Oliver Geden**[6] ✉, **Glen P. Peters**[7] ✉ **& Eve Tamme**[8] ✉

[1]School of Engineering, Tyndall Centre, University of Manchester, Manchester, UK. [2]Centre for Climate and Energy Transformation (CET), University of Bergen, Bergen, Norway. [3]The Centre for Environment and Development Studies (CEMUS), Uppsala University, Uppsala, Sweden. [4]Department of Environment and Sustainability, University at Buffalo, Buffalo, NY, USA. [5]Fossil Economy Program, Center for International Environmental Law (CIEL), Berlin, Germany. [6]Research Cluster Climate Policy and Politics, German Institute for International and Security Affairs (SWP), Berlin, Germany. [7]CICERO Center for International Climate Research, Oslo, Norway. [8]Climate Principles, Tallinn, Estonia.

✉e-mail: kevin.anderson@manchester.ac.uk; hbuck2@buffalo.edu; lfuhr@ciel.org; oliver.geden@swp-berlin.org; glen.peters@cicero.oslo.no; Eve.Tamme@climateprinciples.com

Published online: 16 November 2023

References

1. IPCC *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Shukla, P. R. et al.) (Cambridge Univ. Press, 2022).
2. Bergman, A. & Rinberg, A. in *Carbon Dioxide Removal Primer* (eds Wilcox, J. et al.) (2021).
3. Smith, S. et al. *The State of Carbon Dioxide Removal* (Smith School of Enterprise and the Environment, 2023).
4. van Vuuren, D. P. et al. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Clim. Change* **81**, 119–159 (2007).
5. Reiner, D. M. Learning through a portfolio of carbon capture and storage demonstration projects. *Nat. Energy* **1**, 15011 (2016).
6. Fuss, S. et al. Betting on negative emissions. *Nat. Clim. Change* **4**, 850–853 (2014).
7. Anderson, K. & Peters, G. The trouble with negative emissions. *Science* **354**, 182–183 (2016).
8. Geden, O. Climate advisers must maintain integrity. *Nature* **521**, 27–28 (2015).
9. Babiker, M. et al. in *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Shukla, P. R. et al.) 1245–1354 (Cambridge University Press, 2022).
10. van Asselt, H. & Green, F. COP26 and the dynamics of anti-fossil fuel norms. *WIREs Clim. Change* **14**, e816 (2023).
11. Dooley, K. & Kartha, S. Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. *Int. Environ. Agreem. Politics Law Econ.* **18**, 79–98 (2018).
12. Sekera, J. et al. Carbon dioxide removal — what's worth doing? A biophysical and public need perspective. *PLoS Clim.* **2**, e0000124 (2023).

13. Rogelj, J., Geden, O., Cowie, A. & Reisinger, A. Net-zero emissions targets are vague: three ways to fix. *Nature* **591**, 365–368 (2021).
14. van Vuuren, D. P. et al. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nat. Clim. Change* **8**, 391–397 (2018).
15. McLaren, D. Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques. *Clim. Change* **162**, 2411–2428 (2020).
16. Cozzi, L., Chen, O. & Kim, H. The world's top 1% of emitters produce over 1000 times more CO_2 than the bottom 1% — analysis. *International Energy Agency* (2023).
17. Geden, O. The Paris Agreement and the inherent inconsistency of climate policymaking. *WIREs Clim. Change* **7**, 790–797 (2016).
18. Markusson, N., McLaren, D. & Tyfield, D. Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs). *Glob. Sustain.* **1**, e10 (2018).
19. Günther, P. & Ekardt, F. Human rights and large-scale carbon dioxide removal: potential limits to BECCS and DACCS deployment. *Land* **11**, 2153 (2022).
20. Bows-Larkin, A. et al. Importance of non-CO_2 emissions in carbon management. *Carbon Manag.* **5**, 193–210 (2014).
21. Rickels, W., Proelß, A., Geden, O., Burhenne, J. & Fridahl, M. Integrating carbon dioxide removal into European emissions trading. *Front. Clim.* **3**, 690023 (2021).

Acknowledgements
G.P.P. acknowledges support from the European Union's Horizon Europe Research and Innovation Programme under grant agreement number 101056306 (IAM COMPACT). O.G. receives support from the Federal Ministry of Education and Research (grant numbers 03F0898E and 01LS2101A). L.F. acknowledges funding from a number of foundations and individual donations that support The Center for International Environmental Law (CIEL; see https://cielannualreport.org/supporters/). K.A. acknowledges the following colleagues for their long-term engagement on CDR issues: A. Larkin, D. Calverley and I. Stoddard.

Competing interests
The authors declare no competing interests.

Additional information
Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Related links
Carbon Brief Guest Post: https://www.carbonbrief.org/guest-post-what-the-tiny-remaining-1-5c-carbon-budget-means-for-climate-policy/
IPCC Special Report on 1.5 °C Warming: https://www.ipcc.ch/sr15/
Tyndall Production Phaseout Report: https://research.manchester.ac.uk/en/publications/phaseout-pathways-for-fossil-fuel-production-within-paris-complia