OPINION

Climate policymakers and assessments must get serious about climate engineering

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Climate engineering (CE)—the intentional, global-scale modification of the environment to help offset the effects of elevated greenhouse gases—appears able to reduce climate-change risks beyond what's possible with mitigation and adaptation alone. Furthermore, the large-scale use of CE is probably essential for achieving prudent climate-change limits, including the Paris target of limiting the average global temperature rise to 1.5–2.0 °C. This conclusion appears unavoidable based on the current level of global greenhouse-gas emissions and the long time-constants of the climate system and the human energy system (e.g., the long atmospheric lifetime of carbon dioxide and the time required for large-scale deployment of new technologies). CE may also enable integrated climate-response strategies that reduce risks in ways not otherwise achievable.

At the same time, such strategies cannot replace mitigation or adaptation, which remain essential responses to the severe risks that climate change poses. And the various forms of CE, both carbon removal and sunlight-scattering solar geoengineering, pose novel, significant, and uncertain risks (1–5).

In view of CE's high stakes and complex implications, which offer the prospect of great benefit or harm, its use urgently needs serious, critical investigation. This has not happened. The treatment of CE thus far in climate research, assessment, scenarios, and policy debates has been at best selective and insufficient; at worst, the subject has been misrepresented or ignored.

Serious examination of CE would challenge many comforting presumptions of climate policy debates and assessment processes, but this challenge must be met. There are at least three major reasons that policy and assessment bodies must take better account of CE. First, as stated, CE might prove crucial in managing climate risks. Second, as climate-change impacts mount, vulnerable states will likely propose, demand—or simply start—operational CE interventions; better to examine CE and its implications before this happens (6). Third, decisions have already been made, in Paris and elsewhere, that implicitly rely on future deployment of some forms of CE—having committed to the ends, knowingly or not, states must now take stock of the means (7, 8). Multiple national and international bodies will have to carefully consider CE, but the most immediate responsibility falls on the Intergovernmental Panel on Climate Change (IPCC), in its current special report on the Paris 1.5 °C target and the subsequent Sixth Assessment Report (9).

Due to the complex implications of climate engineering, its use demands immediate, serious, critical investigation at the highest levels. Image courtesy of Shutterstock/idiz.

Engineering Climate Risk Reduction

Broadly speaking, there are two types of CE: actions that increase the scattering of incoming sunlight (solar geoengineering) and actions that increase the emission of thermal radiation to space, of which the most widely discussed are various ways to remove carbon dioxide from the atmosphere (1–3). Although these are very different technologies, both have the effect of decoupling future climate from cumulative carbon dioxide emissions (10), which is why the Paris decisions depend on them, even if not explicitly.

At the time of the Paris agreement, the allowable budget of cumulative future emissions consistent with likely meeting the 2 °C target was estimated at 800 to 1,200 $GtCO_2e$ (11). That's 20 to 30 years of emissions at the current 40 $GtCO_2e$ per year. Budgets for 1.5 °C have received few analyses thus far but will clearly be much tighter: early estimates suggest approximately

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200 $GtCO_2e$, or 5 years at the current emissions rate (12). Rapid, ongoing progress in solar, wind, and other renewable technologies, while a welcome and important step toward decarbonization, falls far short of what is needed to keep the world within these budgets. Continuing shortfalls of actual mitigation efforts, including the lamentable US retreat from its Paris commitments and planned emissions regulations, only make this dire situation worse.

The present reliance on CE emerged in the run-up to Paris, as officials asked researchers for scenarios consistent with 2 °C. Most of the Integrated Assessment Models (IAMs), which project emissions and related socioeconomic conditions, found that the target could not be met via plausible and cost-effective levels of mitigation. To make up the shortfall, modelers added CE in the form of two carbon-removal methods: afforestation and bioenergy with carbon capture and sequestration (BECCS). With these "negative-emissions" technologies included, models allowed overspending the carbon budget over the next few decades, then repaying the resultant debt by removing previously emitted carbon dioxide from the atmosphere later on.

Because these gambles might fail, it is essential for prudent climate-change planning to investigate and consider solar geoengineering.

Considered narrowly, this approach made sense. If the rate of emissions reductions needed to meet strong climate targets is implausible, then either the targets must be relaxed or some form of CE must be invoked. But the treatment of these options in assessments and scenarios thus far has been incomplete and misleading.

The 2 °C model scenarios used in Paris project cumulative carbon dioxide removals of 500–1,000 Gt by 2100 (7, 8). Achieving these removals with BECCS or afforestation would require productive lands of 300–1,000 M Ha, about one to three times the area of India (13). Such a huge land-use footprint is likely to have unacceptable environmental and socioeconomic impacts. Other carbon removal approaches, such as enhanced weathering and direct air capture (DAC), make less intense use of productive lands and so are likely to have lower impacts on ecosystems, livelihoods, and communities. But because these approaches are earlier in development and less well characterized, they were not considered.

Moreover, the way these assumptions were introduced into the policy process—effectively as a technical dodge by modelers who were pressed to generate scenarios in which the 2 °C target, initially agreed on in 2010, still appeared achievable—meant that the scale and significance of these assumed removals was not debated explicitly enough, publicly enough, or at high enough decision levels.

This lack of transparency has fed several serious and persistent misconceptions, e.g., that these scenarios show 2 °C to be feasible by mitigation alone, that the reliance on carbon removal they imply is achievable through familiar and benign land and forest stewardship measures, and that the scale of assumed reliance on these removal methods is reliably feasible and acceptable (14). In fact, these assumptions and the policies based on them represent a high-stakes gamble—and not a good one. Known carbon removal approaches can clearly make contributions that have acceptable social and environmental impacts, but the scale of contributions that can be confidently relied on is on the order of millions of tons per year, not the billions assumed in these scenarios (15).

A Carbon Removal Trilemma

Efforts to meet the Paris targets by using known carbon removal methods present a "trilemma." Three conditions are required for success—scalability, acceptable impacts, and low cost—but identified methods fulfill at most two of them. Good husbandry practices for forests and soils are benign and cheap but cannot scale to the required 10^9–10^{10} tons per year; BECCS is cheap and scalable but carries heavy land-use impacts; and DAC is low impact and scalable but expensive—at least for now. Adaptive approaches that combine the immediate deployment of known methods with research and periodic reassessment can probably expand the scale of acceptable removals (15), but the trilemma will not be readily broken for billion-ton deployments (8, 13).

If policymakers judge carbon removal on these huge scales to be necessary—i.e., if they judge it imperative to further limit climate change, but mitigation can't go fast enough to do it—then absent a breakthrough in some novel method, most of the job must fall to DAC, regardless of cost. And time is not on our side: each year of delay adds another 40 Gt to required future removals.

Why Not Just Cut Emissions Faster?

If such a big gamble on future carbon removal is unacceptable, the first place to look for better prospects is the presumed limits of feasible mitigation. The Paris 2 °C scenarios already assume rapid expansion of efficiency and noncarbon energy sources. But their large carbon removals were mainly driven by cost-minimizing processes in models that favored later removal over more expensive, nearer-term emission cuts, not by explicit judgments that faster cuts were not feasible (16).

But even ignoring cost, the few studies that claim to demonstrate ways to achieve substantially faster and steeper mitigation—fast enough to reach the 2 °C target without large carbon removals—are all suspect for various reasons. They exclude details related to technology performance, capital turnover, investment, policy, and other points necessary to show feasibility; they make extreme assumptions on these matters; or they posit rapid and disruptive societal transformations without explaining how likely these are, how they would come about, or how compatible they would be with liberal democratic societies (17–21). While the limits of feasible mitigation are uncertain, contested, and contingent on social values and political will, the assumptions and omissions underlying these rapid

mitigation scenarios make them a gamble that's just as imprudent as relying on large future carbon removals.

Solar, The Other Geoengineering

Because these gambles might fail, it is essential for prudent climate-change planning to investigate and consider solar geoengineering. There's much to learn about these methods and many grounds for concern. Compared with carbon-removal methods, solar geoengineering is less developed, less researched, and less easily integrated into established ways of thinking about climate change. Some methods offer the prospect of a fast impact, allowing the temperature effects of increased greenhouse gas concentrations to be offset as they happen, rather than decades later. All identified methods, however, offer only incomplete and imperfect correction for carbon dioxide–perturbed climate and only small and indirect redress for other environmental harms of elevated carbon dioxide—notably ocean acidification—while also introducing significant new environmental impacts and risks (1–3). Any use of solar geoengineering would also carry substantial new risks related to how, by whom, and with what aims they are used, posing challenges to international governance both novel and severe (6, 22).

In view of their large potential contributions and risks, both carbon and solar geoengineering should be on national and international decision agendas. But how and when? There are reasonable grounds for concern about either too much political attention to CE too soon or too little too late. An early push for formal international policies on CE would pose clear risks. Actions taken based on uninformed hopes or fears could be regretted later on but hard to reverse (23). Yet consideration of CE has thus far been marked less by any rush to action than by a refusal to look at the prospect based on reflexive aversion or an expectation that it may undermine mitigation efforts.

Avoiding the issue does not, however, make the stark arithmetic of climate budgets go away, nor does it diminish the risk of a future crisis as some states facing severe climate impacts rush to deploy CE. Moreover, the experience of the Fifth Assessment Report and Paris shows that failing to speak clearly about the gap between climate targets and mitigation prospects, and the potential for CE to narrow that gap, does not protect against policy decisions that rely on CE. It merely obscures them.

Expanded Research, Responsible Assessment

Governments need to stop ducking the CE issue and demand information that better informs the decisions they must make that concern CE, now and in the future. Several distinct types of advice and input are needed. Among the most challenging will be advising on the high-stakes but ill-defined governance challenges posed by solar options. These need exploration and consultation in broadly representative bodies that are deeply informed by expertise in international relations and institutional design as well as science, yet removed from immediate policy responsibilities. No existing body fits the bill. A World Commission on CE could be a promising first step, given enough government support to establish one with the required mandate, stature, and resources (6, 24).

CE also needs expanded research and increased attention in climate-change assessment and scenarios—processes for which bodies with relevant responsibilities and capabilities already exist. Yet the treatment of solar geoengineering in these processes thus far has been even more inadequate than that of carbon removal. Repeated calls for expanded research, including in several separate assessments specifically targeting CE, have had little effect. And solar geoengineering remains almost completely ignored in broader climate assessments and the scenarios associated with them.

This needs to change fast. CE needs to be fully integrated into mainstream, authoritative climate-change assessments, principally from the IPCC. These bodies must undertake serious, critical, even-handed examinations of specific CE methods, their potential contributions, impacts, risks, and key uncertainties. To responsibly inform policymakers about realistic choices and tradeoffs, both types of CE must also be included—explicitly and systematically—in the climate-change scenarios that organize and structure assessments.

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Scenarios frame discussions on climate change and potential responses by specifying alternative plausible paths for future emissions and associated conditions. In doing so, they support standardized, comparable analyses using climate, impact, and integrated-assessment models (25, 26).

In contrast to the present limited treatment of some carbon removal options, scenarios must be extended to incorporate alternative pathways for all promising carbon and solar methods, in conjunction with alternative mitigation pathways and associated socioeconomic and policy trends. In undertaking these tasks, assessments and scenarios can begin to provide a much-needed framework to clarify choices and inform policymakers about interactions and tradeoffs among mitigation, adaptation, and CE measures and their relationship with alternative climate targets.

Gaps in current knowledge do not justify further delay in taking CE seriously in assessments. Indeed, assessments must explicitly include even less well characterized methods for which research is in early stages, such as direct air capture, enhanced weathering, and most solar methods. They can thereby highlight key uncertainties, their significance, and their relationship with alternative choices, and thus provide more effective guidance for the needed expansion of CE research.

Integrating CE into climate-change assessments and scenarios will likely not yield strong conclusions initially but still must start now. Only by doing so can

researchers and policymakers frame available choices consistently and set in motion the needed mutually reinforcing advances in research, assessments, and policy debates.

The place to begin treating CE more explicitly and seriously is the IPCC special report on the 1.5 °C target, now partway through its work. The increasingly likely need for CE to meet this or other ambitious targets is painful and cannot avoid controversy. Yet it is simply not possible to responsibly assess the feasibility of this target without considering both carbon removal and solar options. Even if time and resource limits allow only preliminary treatment of CE in this report, it can still contribute simply by addressing the issue candidly rather than ducking hard choices through concealment or euphemism. It should aim to raise awareness of the challenges of the Paris targets and the potential contributions of CE, to identify research priorities, and to begin defining new scenarios to support consistent analysis of CE options.

Neither large-scale carbon removal nor solar geoengineering would have any role as part of an ideal response to climate change. But that ship has sailed. The ideal climate response would have required nations to begin serious mitigation 30 years ago, when scientific evidence warranted it. The continued failure to undertake serious mitigation since then has brought about the current situation, in which large-scale future deployment of these contentious and frightening technologies, in some form, is both increasingly likely to occur and increasingly likely to be less damaging to humans and the environment than the available alternatives.

While the slow movement of climate change obscures both the severity of risks already committed and the hard choices coming, this does not excuse competent expert bodies, such as the IPCC, from responsibly and critically examining all potentially useful approaches, including both types of CE. Nor can further delay be justified by the need to await more research. Because assessments strongly shape research agendas, this is a circular argument that would justify indefinite continued delay. If CE options should turn out to be barred or limited by unacceptable impacts or harm not yet identified, states need to know now rather than continuing to implicitly rely on unexamined options.

Whether future use of CE options will be judged desirable or not, there is an urgent need to begin an honest debate about them, while also pursuing mitigation and adaptation with much greater vigor than has been achieved thus far. Not doing so would make already grave climate-change risks even more severe.

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