In ongoing debate over how to slow and stop climate change, the past year or so has seen a large shift of attention and interest toward technological options to remove CO_2 from the atmosphere after it is emitted – options generally lumped under the headings "Carbon dioxide removal" (CDR) or "negative emissions technologies" (NETs).

These terms cover a highly diverse collection of a dozen-odd removal approaches, which differ both in the mechanism by which they remove CO_2 from the atmosphere in the first place (the main division being biological methods that start with plant photosynthesis and chemical methods), and in the subsequent fate of the removed CO_2 (stored in various geological formations underground; in the ocean or seafloor; in forests, soils or other biomass; or in products such as building materials or fuels).

The surge in attention to CDR is a source of some promise, and some alarm. The promise is that CDR can make large contributions to managing climate change – in particular, that it can do so in ways that the familiar forms of climate response – cutting current emissions or mitigation, and adjusting to the changes to reduce resultant harms, or adaptation – cannot.

CDR technologies can provide offsets for those emissions sources that are most difficult or technically costly to reduce, such as (by present assessments) emissions from aviation and some industrial processes. They also offer the unique prospect, if deployed at huge scale, of more than offsetting continuing emissions so net human emissions become negative. If this happens, atmospheric CO_2 concentration would not just stop increasing (the most that emissions cutting can achieve) but would actually decrease, bringing atmospheric concentration and the associated climate back to some previous state, one less perturbed by human activities. That ability to reverse the direction of change is essential both to future "overshoot" scenarios in which the climate is brought back to some target after temporarily exceeding it, and to ambitions for "climate restoration" that would return atmospheric concentrations and climate to some state that is already past – perhaps 400 ppm CO_2 as it stood in 2015, 350 ppm as in the early 1980s, or 300 ppm as in the early 20th century.

For both these reasons, CDR represents a valuable expansion of the set of response options available for climate change – particularly because decades of inaction on emissions cuts has made large-scale CDR deployment virtually essential for achieving prudent climate targets. Nearly 90 percent of the scenarios of future emissions that meet the Paris target of limiting global heating to 2°C above the pre-industrial level (i.e., a further 1.0°C of heating beyond the 1.0°C that has already happened) – and all the scenarios that meet the stronger 1.5°C target – rely on CDR removals so large as to make net anthropogenic emissions negative around mid-century, with total removals on order hundreds of billions of tons CO_2

by 2100 (For comparison present world emissions are 40 billion tons CO_2 per year). CDR thus plays an essential role in the "net zero" emissions targets that many jurisdictions have adopted.

That's the promise. The cause of alarm is that CDR does not avoid the need for large, immediate reductions in emissions – and uncritical reliance on its future promise represents a large gamble on future technological performance, which might not turn out well but which is already distracting from the undiminished need for these reductions.

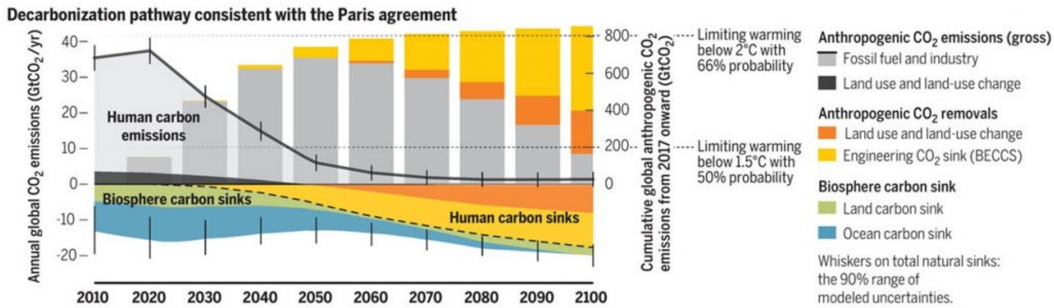
While there is wide variation among CDR options, even the most advanced are at the stage of their first commercial or semi-commercial deployments, and all need substantial further research, development, and assessment to be ready to operate at scale. While multiple approaches promise the possibility of large future removals, all presently exhibit serious limitations and barriers related to various combinations of technological readiness, feasible maximum scale, environmental and socio-economic impacts, and cost.

At present, conventional emissions-reduction measures – further increases in energy efficiency of economies, and further rollout of already available and in-the-pipeline low and zero-emissions technologies – dominate CDR options on grounds of feasibility, scalability, cost, and impacts. Far more reduction opportunities are available now at relatively low marginal costs or equivalent emissions prices – on order ~ \$10 to \$50 per ton CO_2 – than are available, now or soon, from CDR. Moreover, this comprehensive advantage of reducing current emissions over sucking them back out of the atmosphere after they are emitted is likely to remain the case until emissions have been reduced much more than present efforts, to cuts of at least 50 percent, perhaps as much as 80 or 90 percent. The uncertainties in these estimates about future technology prospects are large, such that it is not clear how many emitting activities will make sense to allow to continue, offset by CDR, rather than reducing. But the scale of these residual emissions that are allowed to continue is highly unlikely to be so large as to reverse this ranking – to put CDR ahead of further emissions reductions – any time soon. CDR represents a large potential contribution to climate management options, but also a big gamble that sufficiently large, benign, and cost-competitive options will be available when they are needed later in the century. It would be wildly imprudent to double down on this gamble by continuing half-hearted (or worse) efforts on mitigation.

And that gamble is the problem with current climate debate. CDR is experiencing a period of uncritical enthusiasm and wild exaggeration of capabilities that is obscuring the associated limits and risks, and leading many people to believe, mistakenly, that CDR's "great expectations" have reduced the need for forceful action to cut current emissions.

They have not. Continuing to emit at present high levels is going further and further into debt. Counting on cheap, easy, and unlimited future removals is like counting on some future high-paying job or business success – or worse still, counting on winning a lottery jackpot (that's a little too harsh – the odds of big future contributions from CDR are much better than those in a lottery, but that's still a long way from a sure thing) – to pay off the debt you're incurring.

The figure below shows this nicely. It's taken from [a paper by Johan Rockström and his colleagues in Science] from a couple of years ago. This is a prominent example of the many recent technical analyses that have mapped out scenarios of future emissions and removal trends to achieve the Paris targets, but many others tell equivalent stories. The scenario shown here is estimated to have a 50% chance of achieving the Paris 1.5°C target, and a more than two-thirds chance of achieving the 2°C target. To do so, it assumes deployment of future carbon removals, with year-to-year removals represented by the orange and yellow wedges below the horizontal axis (growing to ~ 20 billion tons/year by 2100) and cumulative removals by the yellow and orange segments of the bars at top right (reaching ~ 600 billion tons cumulative removals by 2100). But even with this extreme scale of removals, look at how rapidly emissions still must fall to achieve these targets, the heavy black line: from 40 Gt/year today, to 25 Gt/year by 2030 and 15 Gt/year by 2040, with continuing decreases thereafter. Even with the huge assumed deployment of CDR, the scale and speed of these reductions dwarf any current efforts and prior achievements.



Analysis by Johan Rockström and colleagues in Science maps out scenarios of future emissions and removal trends to achieve the Paris targets

Why are people relying so strongly and uncritically on being rescued by uncertain future technologies? Partly it's the perennial desire to let future advances solve current problems – a long-standing theme in climate debates and elsewhere. But there are some particular reasons that the prospect of CDR exerts such a dangerous hypnotic effect on thinking about climate change. I find three particularly striking.

First, cutting emissions the familiar way is a regulatory program, which imposes costly requirements on enterprises and citizens. Regulation is costly, difficult, and contentious. The past thirty years of weak mitigation action illustrates just how effectively the targets of greenhouse-gas emissions regulation – the fossil-fuel enterprises and the other businesses, people, and communities that rely on them – have been able to resist and stall this regulatory agenda. CDR, on the other hand, is a set of not-yet-deployed technologies that are highly (although uncertainly) promising, perhaps even essential, for achieving future goals. Pursuing them is thus a program of government research support, subsidies for roll-out and demonstration projects, and other public expenditures. Spending public money to develop something exciting and new is generally easier and less contentious than deploying the state's coercive authority to impose requirements and burdens on something already in operation – even if, as in this case, the total social cost of the latter approach is much cheaper. Or to be more precise, it's easier until the bills come due and the present expenditures have to be covered – but that is a problem for future political leaders, not today's.

The two other reasons for excessive reliance on CDR come from the extreme heterogeneity of CDR options, which present different (and not entirely compatible) attractions – both real and symbolic – to different groups active in climate debates.

On the environmental side, many people are attracted to biological CDR processes, such as forest and soil conservation, which use photosynthesis to remove atmospheric carbon and biological stocks to store it after removal. These approaches – branded "nature-based solutions" – present the attractive symbolism of climate-change interventions that resemble familiar, long-standing conservation practices with multiple benefits. Unfortunately, the attractive symbolism is a highly misleading guide to the feasibility and aggregate impacts of deploying these options at global scale. Even setting aside the strangeness of calling human interventions to remove and store billions of tons per year "natural," these approaches – with a few possible exceptions – appear to be less promising on potential scale, impacts, and cost than more obviously technology-driven removal methods.

On the other side – dare I call it the "anti-environmental" side – there is great enthusiasm among fossil-fuel production enterprises, backed up by large investments, for CDR processes integrated with fossil-fuel production. These processes aim to offset emissions from the processing and eventual burning of fuels by removals, either physically integrated into the fuel production process (e.g., injecting CO_2 into oil and gas reservoirs to enhance production) or conducted elsewhere with accounting linkages. Depending on many details, such integrated fuel production and carbon removal operations could yield fuel products with greatly reduced, or even zero or negative, life-cycle emissions. Such integrated systems hold real promise: indeed, they will be essential if some especially hard-to-cut emissions sectors are to continue. But they also present several serious risks. For example, they may promote indefinite continuation of fossil-fuel production levels that are not warranted on technical, environmental, or cost grounds, by shifting costs from the fuel producer to the treasury via subsidies for CDR development. Even worse, such complex integrated systems will require complex processes of emissions accounting and life-cycle analysis, which will present many opportunities for biased estimation and double-counting, with the result that claims of low or negative full-system emissions are not correct. The present rush of new investments and technology development into linked fuel production and CDR suggests that these options are likely to pursued at scale – and with strict accounting and analysis these can represent real contributions. But it will take great vigilance to ensure that the accounting, analysis, and project operations are scrupulous. And given the limits and uncertainties associated with CDR overall, these options do not warrant any easing up on the primary task of cutting emissions.

Continuing to deploy climate-safe technology to cut emissions is the first task. CDR holds large but uncertain promise, to sustain cuts and continue to negative levels – and it needs vigorous R&D support, to develop and assess options and build capacity. But these efforts must be additional to mitigation, not replace it or distract from its primacy – and the level uncritical enthusiasm, unjustified reliance, and hyped claims swirling around CDR at present presents risks that it will do just that – impairing rather than strengthening the aggregate response to climate change.