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Just a few years ago, carbon removal wasn't seen as something that could be realistically scaled, observed Senator Lisa Murkowski (R-Alaska). "It is now becoming clear that technologies to permanently remove carbon dioxide from the air and the ocean are not only real, but they are needed and they are certainly worth pursuing," she told the Senate Committee on Energy & Natural Resources at the end of July, which held a hearing on the development and deployment of large-scale carbon management technologies.

"When coupled with the increased deployment of low and zero-emission technologies, carbon removal options can help offset "hard-to-abate" sectors and could eventually even help reduce atmospheric carbon dioxide levels," Sen. Murkowski said in her opening statement.

This is an interesting point in the career of large-scale carbon removal: bipartisan recognition from members of Congress that it could eventually reduce atmospheric carbon dioxide levels, and in most projections is necessary (at massive scale) to achieve Paris targets. Maybe we will really do this.

But scaling up carbon dioxide removal (CDR) to the levels that would make a significant difference in the climate would be a tremendous feat. To keep warming to below 1.5°C (2.6°F), according to the Intergovernmental Panel on Climate Change, between 100 billion – 1 trillion tons of CO_2 would need to be removed over this century.

There are a number of ways to remove carbon dioxide, from storing it in ecosystems to speeding up rock weathering processes to pairing bioenergy with carbon capture and storage. One approach which has received a lot of attention lately is direct air capture using chemical processes paired with geological CO_2 storage. Scaling it up to levels that could eventually reduce atmospheric carbon dioxide, though, will take a lot of money and clean energy. Estimates for a direct air capture system that can remove 10-20Gt per year of CO_2 — which is on par with global estimates of curbing warming to 1.5°C — could require 100EJ per year, or about one-sixth of today's totally world energy consumption, and more than triple the share presently provided by renewables. Costs could range from $100-300 per ton of CO_2 captured, so most likely upwards of a trillion dollars, perhaps much more. It's quite an undertaking.

Phasing out this infrastructure, eventually

Considering the huge ramp-up required, it is understandable that the emphasis in scientific analysis and policy has been upon how to get policies and infrastructure aimed at removing carbon up and running.

But there's also another problem we should be thinking about: how to phase it down again. The scale of programs proposed— and increasingly, assumed— involve some period during which removals are so big that they exceed remaining human emissions, so the total stock of CO2 in the atmosphere is being decreased. But at some point atmospheric CO2 will have to be stabilized, which will require that the program and infrastructure of CO2 removal will need to be phased down.

Why is it worth thinking about the need for future phasedown now? The carbon removal enterprise and its policies will create risks of lock-in via actors whose interests favor continuing carbon removal, as we write about in a new paper in *Global Environmental Policy*. We are about to embark on policy for carbon removal, and this should be one of many design considerations. A carbon removal enterprise at climate-significant scale will direct massive resource flows to enterprises that design, build, and operate CDR projects; their employees; and the jurisdictions to whose economies and tax bases they contribute. There will also be a regulatory and policy structure that grows up around them. Climate-significant CDR is a large enough challenge that it will produce many entities which will have a material interest in continuing it.

There are historical analogies hat illustrate the importance of scaling down an enterprise that has completed its job, and the challenges of achieving this, such as that of military demobilization, or phasing out fossil fuels. Large-scale coal production has been going on for two centuries; petroleum for 100-150 years. They employ millions and in some regions form the economic base. But the enterprise is highly resistant to contraction. A carbon removal enterprise might have similar characteristics: a duration of 100-200 years, a similar order of magnitude in revenue flows, particular geographies that favor certain geologies or ecosystems. This analogy shows that phasedown may be socially and politically challenging even if the need is clear.

Near-term considerations

So what can we do now, a hundred or two hundred years before our grandchildren and great-grandchildren might be dealing with this? In general, we should not create conditions that might obstruct future phasedown in near-to-mid-term policy actions. It is hard to foresee conditions so far in advance, but some conditions/ factors tend to persist. At minimum, we should avoid creating conditions that are likely to obstruct future phasedown. Those near-to-mid term policy considerations might include the choice of actors to support, establishing more moderate targets for greenhouse gas concentrations, in that very ambitious targets risk creating a CDR enterprise of such huge scale as to exacerbate phasedown problems; and weighing phasedown considerations among choice of removal methods, noting that those methods that are most readily scalable with flat marginal costs will present strongest challenges to future phasedown.

There are three types of proposed approaches to support large-scale carbon removal: privately profitable business models, extended emissions-pricing policies, and public procurement, as we discuss in our paper. The former presents the most challenges for future phasedown. Policies that put a price on emissions, like carbon taxes or tradeable permit schemes, could be motivating in early stages. But they would face more difficulty when emissions go net-negative and would then need to be redesigned. The third option, public procurement, could facilitate phasedown as it would be a public expense, and contracts could incorporate time horizons.

Even though these challenges seem far-out in time, the point is that managing climate change requires planning on a different time horizon than we currently do. Mitigation, adaptation, and potentially solar geoengineering also would benefit from — and in some instances require — planning with centuries-long time horizons. The need for far-ranging foresight is especially acute with CDR because it will require support from public policies, and the policies that initially support it may be different than the ones that maintain it and phase it out. The need for future phasedown also offers one more reason why rapid and drastic emission cuts are needed: a smaller CDR enterprise will be easier to phase out.