Large-Scale Carbon Dioxide Removal: The Problem of Phasedown

*Edward A. Parson and Holly J. Buck**

Abstract

Most scenarios that achieve present climate targets of limiting global heating to 1.5°–2.0°C rely on large-scale carbon dioxide removal (CDR) to drive net emissions negative after mid-century. Scenarios that overshoot and return to a future temperature target, or that aim to restore some prior climate, require CDR to be rapidly deployed, operated for a century or so, then greatly reduced or phased out. This need for future phasedown presents challenges to near-term policies that have been underexamined. A CDR enterprise of climate-relevant scale will require financial flows of billions to trillions of dollars per year. The enterprise and supporting policies will create risks of lock-in via mobilized actors whose interests favor continuance as well as other mechanisms. The future phasedown need implies suggestive guidance for near-term decisions about removal methods and design of associated policy and business environments. First, variation among methods' scale constraints and cost structures suggests a rough ordering of methods by severity of future phasedown challenges. Second, of the three potential means to motivate removals—profitable products incorporating removed carbon, extended emissions-pricing policies, or public procurement contracts—public procurement appears to present the fewest roadblocks to future phasedown.

Since the 2015 Paris climate agreements, the prospect of removing carbon dioxide from the atmosphere—negative emissions—has become a prominent point of hope, concern, and controversy in climate policy debates. Several methods of carbon dioxide removal (CDR) have been proposed. Prominent approaches include enhancing natural carbon sinks in forests or soils; growing bioenergy crops, then capturing and storing the carbon released when they are burned or processed into fuel (BECCS); enhanced weathering of silicate or carbonate minerals; altering ocean chemistry through alkalinization or related processes; and direct air capture (DAC) through various engineered chemical systems. These approaches exhibit substantial variation and uncertainty in key characteristics, including their development status, costs, projected capacity, and projected impacts and risks (National Research Council 2015a).

* The authors gratefully acknowledge financial support from the Open Philanthropy Project and from the Swedish research council FORMAS (for Holly Buck) as well as helpful comments on earlier drafts by Joshua Horton, Ben Kravitz, Jesse Reynolds, and two anonymous reviewers.

Global Environmental Politics 20:3, August 2020, https://doi.org/10.1162/glep_a_00575
© 2020 by the Massachusetts Institute of Technology

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

Despite these uncertainties, as well as evident global governance challenges, recent model-based scenarios that limit climate change rely heavily on CDR. At the time of the 2015 Paris meeting, most scenarios that limited warming to 2°C deployed CDR—typically using BECCS and afforestation as proxies for all removal methods—at levels of 500–1,000 billion tons of CO_2-equivalent ($GtCO_2e$) cumulative removals by 2100 (Anderson and Peters 2016; Fuss et al. 2014). More recent scenarios in the 2018 IPCC special report suggest that 2°C may be achievable with smaller removals, or even none, but only under highly favorable assumptions of rapid mitigation and low energy demand. For example, one recent rapid decarbonization scenario (Obersteiner et al. 2018) achieves "likely" 2°C[1] while avoiding any technological CDR but requires world emissions to drop by half every ten years. Less rosy assumptions or tighter targets, such as 1.5°C, still require removals on the order of hundreds of $GtCO_2e$ by 2100 (Intergovernmental Panel on Climate Change 2018; van Vuuren et al. 2018). Under any climate-stabilization target, peak annual removal rates—which define the required scale of the removal enterprise—increase with slower emissions reductions, a later start on CDR, and more ambitious stabilization targets. In many scenarios, the required scale-up and subsequent decline of removals is extreme. In most 2°C and 1.5°C scenarios, removal rates reach 5–15 $GtCO_2$ per year late this century (Minx et al. 2018), then decline sharply (Keller et al. 2018). The decline is usually not to zero but to some level far below peak removals, to offset continuing emissions from activities that are recalcitrant to deep cuts, such as some transportation modes or industrial process heat.[2]

This heavy reliance on future carbon removal has triggered a sharp reaction. Scenarios were criticized for gambling on technologies that are not fully developed and tested (Anderson and Peters 2016; Parson 2017); for considering only one or two removal methods; for neglecting potentially severe environmental and socioeconomic impacts; for neglecting the extreme rates of scale-up required (Vaughan and Gough 2016); for not adequately conveying these extreme assumptions or their implications to policy makers; and for various ethical issues, including undermining mitigation incentives, inequitable distribution of effects, and burdening future generations (Carton 2019; Lenzi 2018; Shue 2017). Research on these issues is underway, including increased critical scrutiny of potential impacts and limits, but further research and assessment are needed (Minx et al. 2018).

Carbon removal does not avoid the need for rapid emissions cuts, which remain essential. But if removal can work at the required scale with acceptable impacts, using it in parallel with deep emissions cuts could substantially reduce climate risks. CDR at large scale could also make climate targets achievable that are out of reach with emissions cuts alone or enable a reversal of prior CO_2 increases to restore some earlier level of radiative forcing (Intergovernmental Panel on Climate Change 2018, 19). Although

1. In IPCC conventions for expressing uncertainty, "likely" means a judged probability of at least two-thirds.
2. Estimates of these residual emissions vary widely, depending on cost, technology, and political assumptions (Luderer et al. 2018; Royal Society and Royal Academy of Engineering 2018).

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

not precisely defined, "large-scale" removal is beginning to appear as an explicit policy goal.[3] Some groups are calling for even more extreme removal programs, aiming to return CO_2 from its present concentration of 410 ppm to as low as 300–350 ppm, implying removal rates up to ~10–80 $GtCO_2$/year.[4] With estimated removal costs of ~US$ 1–100/tCO_2 for various methods (Minx et al. 2018, 12), the total cost of peak removals late this century is US$ 5 billion to US$ 1 trillion per year under mainstream scenarios, or up to US$ 10 trillion per year for these extreme (albeit probably infeasible) proposals.[5]

Negative Emissions: The Problem of Future Phasedown

In debate over carbon removal, one long-term risk remains conspicuously unexamined: the problem of future phasedown or termination of the enterprise. Any removal program that draws down atmospheric CO_2 by making net global anthropogenic emissions negative must reliably phase down once it has achieved its aim. This is true both for "overshoot" scenarios that initially exceed and then return to some future target and for grander "climate restoration" efforts that aim to restore some earlier, less perturbed climate with atmospheric CO_2 below present levels. In either case, the period of global net-negative emissions must be temporary, since indefinite continuation of net atmospheric CO_2 drawdown would pose grave risks of reproducing ice-age or more extreme conditions (Lacis et al. 2010). This requirement is sometimes unclear in presentations of removal scenarios because analyses or figures end in 2100, when net emissions are still negative and atmospheric CO_2 is still decreasing.

The need for these future phasedowns of CDR and their policy implications have scarcely been examined.[6] However obvious the need for future phasedown may be today, achieving it when the time comes cannot be assumed to be automatic or easy. An enterprise of this scale will generate economic, bureaucratic, and political interests that benefit from its continuance and can present powerful barriers to reduction or termination. Yet the policy challenges of deciding on a future phasedown, reliably implementing it, and navigating through it—and the implications for near-term policy decisions—have been largely overlooked.

3. See, e.g., Manchin (2019). The Enhancing Fossil Fuel Energy Carbon Technology (EFFECT) Act of 2019 calls for "a Carbon Removal Program for technologies and strategies to remove atmospheric carbon dioxide on a large scale," evaluating technologies on their potential for reductions at a gigaton scale.
4. See, e.g., launch announcement, Foundation for Climate Restoration, available at https://docs.google.com/document/d/1ooV28JmLqGRSXnfSL5zOuwek-DIJnh3bR_Orb6z3_g0/edit, last accessed July 20, 2020.
5. For comparison, world economic output is about US$ 85 trillion (2018 data, available at https://data.worldbank.org/, last accessed July 20, 2020).
6. Some studies have examined phasedowns from perspectives unrelated to policy or politics. For example, studies have modeled the ocean-chemistry and carbon-cycle responses after cessation of long-term carbon removal (Keller et al. 2018; Mathesius et al. 2015). More generally, one scholar has argued that the need for eventual termination of any technological intervention raises ethical issues that should be considered explicitly before it begins (Preston 2016).

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

In part, this neglect reflects a sensible prioritization of the near-term need to promote rapid deployment of CDR while also assessing and managing associated risks. Even the mainstream scenarios in official assessments require rapid scale-up of removals to tens or hundreds of $MtCO_2e$ per year by 2030 (Honegger and Reiner 2017; Nemet et al. 2018). Yet even while pursuing rapid deployment of CDR to address urgent climate risks, prudent long-term planning requires recognizing the temporary nature of the enterprise and building the governance capacity needed to achieve this—at a minimum, not creating conditions that will predictably obstruct future phasedown.

While it may appear remote to worry about a phasedown a century hence for a carbon removal enterprise that does not yet exist, such forethought is necessary for CDR to leave future generations with more, not fewer, options. Moreover, this future challenge can affect multiple near-term decisions about the removal enterprise, including targets for greenhouse gas concentrations, removal methods, participating actors and decision makers, and policy and institutional settings.

CDR as a Sociotechnical Imaginary

A carbon removal enterprise of the scale proposed will be a complex sociotechnical system comparable in scale and complexity to current transport, energy, or agricultural systems, involving multiple linked technologies, processes, actors, interests, practices, expectations, and norms. The linked technical and sociopolitical dynamics of such systems have long been recognized but are receiving increasing scholarly attention in response to rapidly developing disruptive technologies, such as artificial intelligence, and high-stakes environmental issues, such as climate change (Rogge and Johnstone 2017; Stegmaier et al. 2014).

Such systems present complex societal challenges that evolve over multiple decades and thus require a correspondingly long view of impacts, assessment, and governance. The governance challenges they pose do not arise simply from rapid technological change, nor from uncertainty alone, but from the complex linkages among social, political, and technological factors and from the mismatch between advancing knowledge of system behavior and much more limited ability to act effectively on the required long time scales.

The nature of transitions and the aims and challenges of governance in such systems are diverse. Such systems can be subject to sociotechnical lock-in, by which self-reinforcing processes of adjustment and feedback make them resistant to change (Seto et al. 2016; Vergragt et al. 2011). While mechanisms of lock-in include economic and political factors such as actors' material interests, relevant factors can also include interactions among technologies and the organization of related institutions, expectations, and practices in ways that reinforce current practices and resist change (Cairns 2014; Lin 2019; Turnheim and Geels 2013).

In such complex sociotechnical systems, the aim of governance may be to surmount lock-in by creating dynamics that sustain and reinforce a desired

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

large-scale change that is not immediately achievable (Levin et al. 2012). Alternatively, the aim may be to hold to a set of consistent societal goals under uncertain but advancing knowledge and changes in capabilities (Gunderson and Peterson 2008; Schultz et al. 2015). It may be to place advance limits on development of new capabilities or subject them to periodic fundamental reassessments (Baylis 2019; Lander et al. 2019).

Several characteristics distinguish CDR's governance challenges from those of other potentially disruptive technologies and associated sociotechnical systems. First, because relevant technologies and systems are only partly developed and not yet stabilized, CDR has the character of a sociotechnical imaginary: a set of hypothetical capabilities not yet realized that influence present policy debate through claims about their potential capabilities or impacts (Markusson et al. 2018). Second, CDR is a set of technologies explicitly advocated to meet an identified societal need—a technological fix—rather than developed by private actors to advance commercial or other private interests (Parson 2017; Sarewitz and Nelson 2008). Third, as we argue here, CDR presents the unique structure of requiring two large-scale transitions to address societal needs: its initial rapid deployment and growth, and its subsequent phasedown. This need to manage both the development and the subsequent decline provides a unique perspective on the governance of sociotechnical systems and transitions, which can inform understanding of the governance of other emerging technologies that present uncertain mixes of public and private benefits and risks.

In the following sections, we decompose the challenge of enacting an effective exit strategy for carbon removal into two parts, which we illustrate by use of a few analogies. We then explore how these future challenges might inform near-term policies and decisions.

The CDR Phasedown Challenge in Two Parts: Deciding When to Stop

The problem of CDR phasedown can usefully be analyzed in two parts: deciding when to stop and reliably implementing that decision. Deciding when to stop means achieving workable agreement among relevant actors on what atmospheric CO_2 concentration, and thus what expected climate, to return to. The relevant actors will mainly be states, since articulating such a global aim is likely to require authority and stature that only states possess, whether this occurs explicitly under the Framework Convention on Climate Change or some other international body tasked with overseeing CDR, or whether it emerges indirectly from less explicitly coordinated state actions.

It is not clear, however, what states' future preferences regarding a CO_2 and climate stopping point will be. States may only develop such preferences over time, perhaps by retrospectively identifying some specific past time and associated climate that political institutions and elites value. These inchoate preferences may be shaped by the emerging research that proposes optimal climate conditions for prosperity and development (Burke et al. 2015). Rather than being clearly known

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

in advance, these preferences are likely to emerge over time as states and citizens experience climate change and the effects of their adaptation efforts.

States may disagree over stopping points for various reasons, including differences in climate vulnerability or different views of appropriate precaution. Even now, when no government has expressed a view and the question is entirely hypothetical, CDR proponents advocate a wide range of targets, from stabilizing whenever the program starts to returning atmospheric CO_2 to 400 ppm as it stood in 2015, 350 ppm as in the 1980s, or 300 ppm as in the early twentieth century.[7] States will need some process to resolve these disagreements. They might attempt to agree in advance on a future CO_2 and climate restoration target—as they agreed on climate-stabilization targets in Paris—but now with their choice set expanded by the explicit possibility of large-scale removals. In view of emergent state preferences and associated uncertainties, however, such advance agreement would be hypothetical and hard to secure against subsequent revision. Alternatively, states might converge on a target via some implicit bargaining process analogous to a median-voter rule: as atmospheric CO_2 decreases, states switch from supporting to opposing further reductions as they pass through their preferred points.

No matter how these matters are eventually resolved, present uncertainty about state preferences over stopping points together with the difficulty of binding future state actions suggest that near-term ability to constrain these future choices is weak. As a result, this part of the phasedown problem appears to have only limited implications for near-term decisions—beyond the exhortation to recognize that such decisions will eventually be needed. This is not the case, however, for the second part of the phasedown problem.

Reliably Implementing the Stopping Decision

While the challenge of choosing an end point for CDR mainly concerns state preferences and actions, the challenge of implementing an agreed stopping point requires unpacking state decision-making to consider nonstate actors and diverse technical, political, and cultural factors, with particular focus on conditions and interactions that might contribute to lock-in (Seto et al. 2016; Vergragt et al. 2011). A removal enterprise of the proposed scale will direct huge resource flows to the enterprises that design, build, and operate removal projects; the people they employ; and the jurisdictions to whose economies and tax bases they contribute. In turn, removal enterprises will develop ecosystems of other related businesses and governmental bureaus that regulate the enterprises and manage related policy frameworks. All these actors will have strong material interests in continuing removals. Moreover, the proposed scale of the enterprise implies that these actors are likely to be sufficiently numerous, rich, and self-identified to mobilize and effectively defend their interests. These interests may be especially powerful if CDR is distributed nonuniformly, such that removal activities comprise a

7. See Concurrent Resolution 137, 115th Cong., 2nd Sess., September 25, 2018.

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

substantial fraction of the revenues, employment, and tax base in some jurisdictions. Even assuming clear agreement on a stopping point, one cannot assume that when this point is reached, the world can simply say to all these actors, "Thank you for your service; that will be all."

Moreover, certain other structural characteristics of CDR may interact with these political and economic interests to reinforce efforts to resist future phasedown (Cairns 2014; Lin 2019; Turnheim and Geels 2013). For example, the prospect of uncertainty and disagreement over the preferred stopping point will aid efforts to oppose stopping by making any particular concentration target or stopping point appear arbitrary. Especially if the capital and skills used in CDR have limited alternative uses, then at any given time a further incremental delay in phasing down will appear easier than taking large immediate losses by stranding those assets. It is even possible that over the long duration of a CDR program, habits and perceptions will adjust to such a degree that the initial mission and the necessity of eventually ending it may be forgotten.

Related Problems and Historical Analogies

The problem of phasing down CDR will be novel. Human institutions have never previously faced an explicit choice of greenhouse gas concentrations, because the possibility of this choice is a consequences of a newly recognized control capability. Yet the problem is not completely without precedent. It has some historical analogies, and has common characteristics with other current and emergent challenges (Buck et al., 2020).

For example, the problem of choosing a CO_2 and climate target resembles, albeit at larger scale, the selection of restoration targets for habitats and ecosystems. These choices illustrate the futility of seeking any objectively optimal target and the unavoidable centrality of political and social values to these choices—and also, more hopefully, the possibility of reasoned debate about these (Jørgensen 2015). In many settings, restoration decisions for degraded lands and endangered species have had to address trade-offs between human uses and ecological history and function, as well as concerns about political feasibility in the context of pre-existing degradation that tend to weaken ambition. Ambitious conservation and restoration aims may be further undermined if human preferences adapt to the novel ecosystems brought about by human disturbance (Hobbs 2017).

More broadly, planning for future CDR phasedown is an instance of an emergent class of decision problems that require considering constraints and consequences over longer time horizons than human institutions are skilled at addressing. Such problems are new because they arise from the conjunction of strong human influences on slow dynamic processes and rapidly increasing—albeit still uncertain—knowledge about these processes. Managing climate change is a prominent example, since effective response will require a program of sustained policies, investments, and actions over more than a century. Although climate change is often described as a decision problem marked by deep uncertainty

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

about future conditions, this is somewhat misleading: climate's novel challenges arise less from uncertainty than from increased knowledge about long-term consequences of choices without a commensurate increase in the ability to manage these consequences. Similarly, one major concern about solar geoengineering as a potential component of climate response (National Research Council 2015b) is that abrupt future termination after long-standing use would trigger rapid and disruptive climate change (Jones et al. 2013; Parker and Irvine 2018; Trisos et al. 2018).

The CDR phasedown problem also has historical analogies—activities that, after operating at large scale for some time, must be reliably phased down despite predictable forces favoring their continuance. One potential analogy, albeit usually at shorter time scale, is military demobilization following conflict. Although wartime analogies for climate response are sometimes inapt, the required rapid buildup of mitigation effort and CDR does have significant similarities to mobilization and economic conversion at the start of a major conflict such as World War II. Subsequent demobilization and reconversion to civilian production are readily achieved when the end of the conflict is clear, given strong domestic interests in bringing the soldiers home and ending the killing and spending. But under other conditions the transition can be more difficult, such as when a conflict ends in a condition other than clear victory, when objectives are unclear or subject to mission creep, or when powerful domestic factions have interests in maintaining a war footing (Ledbetter 2011). In this regard, phasing down CDR may more closely resemble the difficult situations, such as historical wars that lasted decades to centuries or the current protracted and ambiguous US engagement in Afghanistan.

With some historical irony, the closest analogy to future CDR phasedown may well be the fossil fuel production enterprise that created the climate change problem. Large-scale coal production has operated about 200 years, large-scale petroleum production about 100–150 years—both periods long enough that no living person remembers a time before these were central pillars of the economy. Worldwide fossil production generates revenues of about US$ 3 trillion per year and employs about 10 million people.[8] Production is unevenly distributed due to heterogeneous resource endowments, so fossil production provides most of the economic base in many regions, including a few nation-states (Dessler and Parson 2019). Over the lifetime of their exploitation, fossil fuels have brought enormous societal benefits. They have also experienced a gradual shift in their benefit–cost balance over time, as other energy technologies have developed and as the scale of their environmental harms has emerged. Now, with severe climate change looming, the compelling societal interest in greatly reducing or eliminating them is beyond dispute.

8. IBIS World Industry Reports, Global Coal Mining (B0511-GL, November 2017) and Global Oil and Gas Exploration and Production (B0531-GL, March 2018). There are no estimates of future employment in carbon removal, although informal estimates of capital–labor mix in technologies now used and in development suggest a wide range of employment to revenue ratios, from somewhat lower than current fossil production (for direct air capture) to substantially higher (for forest management, soil sequestration, and BECCS)—except insofar as AI-driven automation greatly reduces employment in all these activities.

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

Yet even taking small steps to contract the enterprise has been acutely difficult. Fossil interests mobilized early to defend continued increases in exploration and production, even before the first prominent statements of scientific concern about climate change (Center for International Environmental Law 2017; Oreskes and Conway 2010). They have effectively exploited real uncertainties over the precise timing and severity of climate risks and the relative merits of various responses to oppose any measures to reduce emissions. They have taken advantage of the collective-action character of the problem to denounce any mitigation efforts as ineffective in the face of continued emissions elsewhere (Parson 2015). And they have waged a successful, decades-long rhetorical attack on well-established scientific knowledge and assessment bodies.

A carbon removal enterprise of the scale proposed would resemble the historical fossil fuel production enterprise in a few ways. The CDR program would be of similar duration, 100–200 years, probably leading to a similar degree of routinization of the activity and loss of memory of a time when it was not present. It would be of a similar order of magnitude in revenue flows, perhaps also employment. (Some proposed removal methods appear substantially more labor intensive than fossil production and processing, some less.) Given its vast scale and broad, probably uneven jurisdictional distribution, participating actors would have strong interests in defending its continued operation and political resources to effectively advance those interests—even given clearly established global risks from indefinite continuation that increase over time. In addition to the political power of their numbers, distribution, and revenues, actors seeking to extend CDR could deploy two arguments closely parallel to those now used to oppose regulatory restrictions on fossil fuels. First, there will remain uncertainty over the implications of different CO_2 levels and thus disagreement over the preferred target level. Second, phasing down CDR would impose losses of revenue, employment, and tax base on individual projects and jurisdictions in order to reduce global risks, and so would be subject to collective-action problems. Phasedowns anywhere could be made futile by removals that continue or expand in other jurisdictions. By making this analogy, we do not claim that the temporary lifetime of fossil fuels should have been foreseen and planned for in 1850: the societal harms of fossil fuels only became clear over time, as their scale expanded and knowledge advanced. But the situation of CDR today is different, because of increased knowledge and recognition of the scale of human impacts—and thus does carry responsibility to plan for its future phasedown.

Near-Term Implications: Removal Methods

The fossil fuel analogy illustrates how future phasedown may be difficult or obstructed even if the need is clear but provides little guidance on specific challenges or how to surmount them. These will depend on details of the removal enterprise; the methods used; and the policy, economic, and social context in which it operates. How these characteristics will evolve over the life of the removal

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

enterprise is uncertain, yet a few features that appear likely to persist suggest some guidance on how to preserve opportunities for future phasedown. These pertain to both alternative removal methods and to alternative policy environments to promote removal.

Among alternative removal methods, the challenge of future phasedown will vary with methods' scale constraints and cost structure. Once any method is effectively established with a viable business model that covers costs, obstacles to future phasedown will be greater for methods that present only weak scale limits, or none, or that exhibit flat or declining marginal costs. Based on these criteria, present knowledge of alternative removal methods suggests they can be grouped into five classes, which vary systematically in the severity and degree of uncertainty of concerns they pose for future phasedown. These are summarized in Table 1.

Terrestrial biological methods such as forest and soil conservation offer relatively easy near-term removal opportunities, at costs as low as a few dollars per ton CO_2 on favorable sites. These methods appear likely to have increasing marginal costs, however, due to heterogeneity of sites and projects, with their total capacity eventually limited by sink saturation. Sequestration in such biological reservoirs will also be vulnerable to disturbance and thus impermanent (Fuss et al. 2018; National Research Council 2019). These methods are a major focus of current policy and promotion efforts, partly due to their having been framed as "natural" (Griscom et al. 2017), but their limited scale and impermanence are likely to redirect efforts over time toward more scalable and secure methods. Scale limits also suggest that these methods do not raise serious concerns about eventual phasedown, despite present enthusiasm and low costs.

BECCS, the most prominent removal method in recent assessments, differs from other land-based methods by combining initial atmospheric removal through photosynthesis with subsequent geological sequestration. Estimated costs of BECCS are intermediate and widely variable, from ~US$ 30 to US$ 200/tCO_2. Large-scale use of BECCS raises significant concerns about environmental and socioeconomic impacts, however, which suggest its scale will be limited by competition with food production for arable land, water, and nutrients, whether this limitation operates through market-driven price effects or policies and regulations (Fuss et al. 2014; Rau et al. 2018; Smith et al. 2016). This limit will apply to the total land area used, however, and so will constrain annual removal rates rather than cumulative removals. BECCS thus presents greater concerns about future phasedown than terrestrial biological methods that face absolute removal limits due to sink saturation.

Other methods, including enhanced mineral weathering and DAC, appear to be much less scale constrained. Enhanced weathering resembles BECCS in having a large land-area footprint, but it does not need arable land and so is less likely to compete with food production. It will face site heterogeneity and potential scale constraints, based on such factors as the volume, accessibility, and distribution of suitable mineral materials and available surface area to spread them out and expose them to weathering. The slope of its marginal costs and the presence of

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

Table 1
CDR Methods and Their Phasedown Challenges

Method	*Present Characteristics*	*Future Phasedown Concern*
Terrestrial bio methods (forests, soil, biochar)	• Low cost • Supported as "natural" • Site heterogeneity, increasing marginal costs • Scale limited by sink saturation • Impermanent, subject to disturbance	Low • Absolute scale internally limited by impermanence and saturation
BECCS	• Costs moderate, variable • Competition with food production limits removal rate • Site heterogeneity, increasing marginal costs • Produces energy, profitable operations possible	Moderate • Limits on annual rate, not cumulative removals • Profitable operations may hinder phasedown
Enhanced weathering	• Early technical stage, characteristics uncertain • Heavy land footprint but not cropland • Site heterogeneity, increasing marginal costs	Uncertain—moderate? • Feasible scale, limits uncertain • Profitable operations unlikely—would need policy support
Direct air capture	• High cost • Potential scale large—weak limits from sequestration sites • Limited site variation—flat marginal costs	Uncertain—high? • Viable business models need policy support or linkage with products • Use with EOR reduces net removals, reduces phaseout concern

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

	• Integration with products—possibility of profitable operations	• Use with sequestration has weak scale limits, flat marginal costs: severe phaseout concerns if self-sustaining business model established, not otherwise
Marine chemical methods	• Early research, performance and impacts uncertain • Estimated costs low but highly uncertain • Different methods may have environmental impacts or co-benefits • Potential scale very large • International legal obstacles	Uncertain—highest? • Potential for low direct costs, co-benefits, feasible scale might be vast • Viable business models require policy support, no evident link to products • Marginal costs probably flat for viable approaches • International legal setting, business models—may hinder start but lock in once established

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

scale constraints will depend on these factors. While these are presently uncertain, they may be expansive enough to present still greater concerns about future phasedown.

DAC can use unproductive or previously converted lands and is unconstrained by surface geology. It can coexist with other land uses, provided these are not impaired by local CO_2 reductions. As a result, the major factor differentiating sites or limiting removals will be access to geological sequestration. While DAC's present cost estimates are well above those of other methods (present estimates range from ~US$ 100 to US$ 300/tCO_2; Keith et al. 2018; Minx et al. 2018; Rhodium Group 2019), these factors suggest less site heterogeneity, and thus flatter marginal costs, than the methods discussed above. For these reasons, DAC more closely resembles a classic backstop technology than other removal methods. These weak scale constraints and flat marginal costs suggest that if a viable business model for large-scale DAC operations is established, there would be few technical or economic barriers to its continuation or expansion. It would thus present still greater concerns about future phasedown, especially if learning and economies of scale bring large sustained cost reductions.

Finally, several potential methods for marine carbon removal have recently been proposed or gained increased attention, including cultivating marine plants for BECCS, adding constrained nutrients or alkalinity to surface waters to increase carbon uptake, or direct CO_2 disposal in marine sediments or the water column (Lenton 2014; Renforth et al. 2015). These have received less study than other methods, and estimates of their cost and capacity vary widely (Fuss et al. 2018; Rau 2019). Some of these are claimed to offer extremely large sequestration capacity, even larger than projected cumulative emissions, perhaps with low and flat marginal costs. To the extent these scale and cost speculations are correct, these methods would present the greatest grounds for concern about future phasedown.

While present estimates of scale and cost characteristics offer this rough ordering of alternative removal methods by the degree of concern they present for future phasedown, these estimates are sufficiently uncertain that their implied guidance for near-term policy and decisions is relatively nonspecific. In contrast, the implications of alternative institutional and policy settings, with associated business models for removal enterprises, appear to be stronger and more specific.

Near-Term Implications: Incentives, Business Models, and Policy Environments

Large-scale carbon removal is costly and likely to remain so. Present policies and proposals to promote removals largely follow familiar models of R&D support, but these are unlikely to be sufficient to promote rapid scale-up and continuance of the enterprise (Rhodium Group 2019). Achieving this will require viable business models for large-scale operation and policy environments able to support these.

Proposed approaches to support projected large removals are of three types: privately profitable business models, extended emissions-pricing policies, and

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

public procurement. These three approaches are conceptually distinct and rely on different revenue sources but can coexist in practice. For example, different approaches could provide distinct but additive revenue streams for particular removal operations, or could serve concurrently as the primary source of revenues, incentives, and coordination for different projects, in the same or different jurisdictions. It is also possible that the role and relative contributions of the approaches could shift over the life of the removal enterprise. The three approaches present distinct implications for the severity of concern about future phasedown, and thus different guidance for near-term policy choices.

Motivating Removals Through Privately Profitable Business Models

Some removal methods generate private benefits in addition to removing carbon, by improving current products and processes or by incorporating removed CO_2 into marketable products. BECCS produces energy in addition to sequestering carbon; soil carbon sequestration and biochar can enhance soil quality and crop productivity. There are also multiple proposals in development for carbon capture and use, which would derive economic value from the captured CO_2 by using it for enhanced oil recovery or incorporating it into building materials, fuels, or other products (Sanchez and Kammen 2016).

The most expansive visions for climate restoration rely on assumptions that some of these business models, particularly those that produce fuels or building materials, can profitably expand to a climatically relevant scale of billions of tons per year (Gt/year) (National Research Council 2019). While this model may be effective in initially establishing some removal approaches, its viability in supporting operations of such large scale over a century or more is less clear, for three reasons. First, it must surmount any commercial disadvantages from using removed CO_2: products incorporating removed CO_2 would have to outcompete conventional alternatives on cost or performance by enough to offset the capture cost. Second, it must be truly carbon negative based on reliable full-system emissions accounting, even in the presence of strong incentives for bias and double-counting (Tanzer and Ramírez 2019). Third, it must be scalable to Gt/year removals (or at least hundreds of Mt) and commercially sustainable at those levels. If these conditions can be achieved and sustained, that is good news for the immediate challenge of rapidly scaling up removals, because once such activities are demonstrated to be commercially viable, they will tend to expand and persist through market forces alone.

This approach, however, also presents the most serious challenges for future phasedown. It thus most closely resembles the historical analogy of fossil fuel production, in that profitable removal operations would not require continuing policy support. If such an enterprise grows large enough, it is plausible that it may also gather the political strength to effectively resist threats, not just from changes in law or policy, but also from market displacement by alternative products and processes. We judge it unlikely that such conditions will apply for

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

operations of the required scale through the required century-odd period of removals, but there is enough uncertainty on these points that we cannot reject the prospect as implausible. Consequently, even while promoting vigorous early expansion of CDR, policy makers must stay vigilant for emergent conditions that could make continuing large-scale removals profitable without policy support. If such conditions are present as the end of the removal period approaches, they will represent obstacles to phasedown that must be overcome through regulation or other external pressures.

Motivating Removals Through Extended Carbon-Pricing Policies

A second approach to supporting carbon removal would be through policies that put a price on emissions, such as emissions taxes or tradable-permit systems. While such policies are already widely but weakly enacted in many jurisdictions to provide incentives for emissions reduction, applying them to removals would require substantial design changes, including greatly expanded scope. Most present mitigation policies cover only emissions from some subset of existing sources, often large final emitters. Although pre-emissions carbon capture and sequestration is sometimes covered by such policies, net sinks and removals separate from existing emissions sources are not. Including these would require modifying policies to let funds or credits flow in both directions. Under an emissions tax, net emitters would make payments to the treasury, while net removers would receive subsidy payments at the same rate per ton. Under a cap-and-trade system, permits would be surrendered for emissions and generated for removals.

The challenge for such policies promoting near-term CDR is the great heterogeneity among removal methods in cost and technological readiness, including present high costs, uncertainties, and development lead times for those methods that appear most scalable (Parson 2017). An alternative emissions-pricing model that can address such heterogeneity is provided by regulatory policies that impose narrower mandates with associated exchange mechanisms. For example, California's low-carbon fuel standard (LCFS) already provides an incentive strong enough to motivate early development of DAC in conjunction with synthetic fuel manufacture (Keith et al. 2018; Parson et al. 2018; Rhodium Group 2019). The LCFS puts a limit on the life cycle emissions intensity of transport fuels, implemented through a tradable allowance market. As an intensity standard, the policy is equivalent to simultaneously taxing fuels with emissions above the limit and subsidizing those below. Because the tax and subsidy can partly offset each other even within a single gallon of blended fuel, allowance prices can reach levels that appear politically infeasible for broader emissions-pricing systems—above US\$ 200/tCO_2 in early 2020—yet have only a small effect on retail fuel prices. Other policies that use emissions prices in a narrow sectoral setting have been proposed as CDR incentives, including variants on renewable electrical portfolio standards or mandates for fossil fuel producers to pay to remove some fraction of the life cycle emissions from their products (Chavez 2018). These policies can generate high emissions

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

prices to motivate CDR, but they achieve this by imposing regulatory mandates on the emissions associated with fuels or other products in commerce. They can thus readily motivate CDR as part of low-carbon displacement of emissions, but their narrow sectoral targeting makes them awkwardly designed to support economy-wide net-negative emissions.[9]

As removals expand to the point of driving net emissions negative, any policy based on emissions prices would require major redesign. The emissions price would then have two jobs: setting the level of continuing residual emissions, and supporting the targeted levels of CDR from whatever mix of lower- and higher-cost removal methods is then in use. Moreover, as net emissions go negative, an emissions tax would turn from a net revenue source to a net public expenditure. It would thus come to resemble a public procurement system, except with payments set at a fixed rate per ton removed rather than established separately for each project. They would thus give large rents to low-cost removal methods.[10] A tradable-permit system would require larger design changes, because permits could no longer be issued for all removals when these exceed emissions.[11] Taxes or other regulations would still be needed to control residual emissions, but the subsidy to removals would have to be reduced in level or narrowed in scope.

Motivating Removals by Public Procurement Contracting

The third approach to supporting carbon removal is public procurement. Governments could contract for removal with businesses or other organizations, or conduct removals through their own agencies, with public funding and under administrative control. As with other procurement, various contractual arrangements would be possible, for example, standard offers at fixed prices per ton, similar to the fixed emissions-price policies discussed earlier, or more complex, individually tailored agreements to take account of different technologies' cost structures, development status, and technological risks.

Relative to the other two, this approach might be harder to start, because public expenditures are more visible, and thus more likely to generate political opposition, than payments integrated into other policies. But if sustaining the removal enterprise requires indefinite continuation of large public payments—

9. These policies could support net-negative emissions if targeted activities were compelled to achieve net-negative emissions themselves, rather than only pursuing net-negative economy-wide. For example, the LCFS's target emissions intensity could in principle be reduced below zero, provided the policy's scope is broad enough to cover CDR opportunities that can generate the needed number of credits. Imposing such a net-negative target on any single product or sector rather than the economy would, however, carry significant risks.
10. This situation would arise if low- and high-cost methods, e.g., BECCS and DAC, operate in parallel but the low-cost one is scale constrained by policies to protect food production rather than by price effects.
11. One possible response would introduce an exchange coefficient between permits granted for removals and permits required for emissions, but this coefficient would need repeated revision in response to changes in the realized and desired balance between removals and continuing emissions.

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

that is, if no other funding model emerges over the life of the removal enterprise that is less visible and politically vulnerable—these same factors would facilitate the phasedown. Contracts for each removal project could readily incorporate limited time horizons to provide assurance that projects can operate profitably for long enough to amortize their investments without continuing indefinitely thereafter. Continued operations after the end of initial contracts could be separately negotiated as desired, again with limits on duration or cumulative quantity removed. This greater flexibility relative to uniform emissions-pricing policies would also come with greater bureaucratic risks. Long-term relationships between officials and contractors would risk regulatory capture, leading to weak regulator judgments, not only about permit and contract terms (which would waste public funds), but also about the continued need for removals, which would increase the difficulty of phasedown.

Conclusions

It may seem remote and speculative to discuss conditions for phasedown of CDR a century or more hence, when the present need is to develop and expand it. But managing climate change requires a long time-horizon. Mitigation and adaptation are also century-scale challenges that require planning and sustained action over longer time and spatial scales than political and legal institutions are accustomed to considering.

The governance challenges of CDR have some commonalities with other emerging technologies, and some key differences. A major difference arises from the fact that CDR is being driven by anticipation of public need, not by private commercial benefits. A CDR enterprise of the required growth rate and scale is unlikely to develop privately but will very likely require support from public policies. As a result, CDR policies must manage a sharp tension: addressing both the compelling near-term need to support rapid growth of removals and the foreseeable need to phase them down in the future—neither of which is likely to occur through market dynamics alone. The foreseeability of this entire life cycle creates a unique responsibility to anticipate and plan for phasedown of the enterprise even while vigorously promoting its initial growth.

CDR, like other climate responses, requires a long-term view of risks and impacts in making current decisions. For example, the need for future phasedown provides an additional reason to cut emissions immediately and aggressively to limit the scale of removals required, because the challenges of controlling and phasing down removals increase with the size of the enterprise. Similar reasoning supports starting and scaling up removals earlier, to spread any cumulative removal target over a longer period and so reduce the peak rate of removals and scale of the enterprise (Obersteiner et al. 2018). Even if these efforts succeed at reducing the peak scale of CDR, however, future phasedown will remain necessary—and challenging to achieve—following any period of net-negative

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

emissions. This suggests several preliminary observations about CDR methods, management, and policy environment.

Removal methods that are most tightly constrained in cumulative removals, or that have the most strongly increasing marginal costs due to site and project heterogeneity—such as forest management, soil sequestration, and possibly BECCS—present the smallest concerns about future phasedown. Less sink-constrained removal methods, or those with flat or declining marginal costs—which may include DAC, enhanced weathering, and various marine methods—present more serious phasedown concerns. There is thus a tension: the methods most promising for large-scale expansion are also likely to present the strongest challenges to future phasedown. Rather than systematically favoring some methods over others, this tension suggests that policies to promote removals should include provisions for future controls, especially for those methods that present the strongest phasedown concerns. Methods with high spatial heterogeneity raise different phasedown concerns. These are likely to be concentrated, and thus politically powerful, in certain jurisdictions. If they are sufficiently powerful to resist policies to promote phasedown in their jurisdictions, multijurisdictional policy frameworks may be required.

Considering policy frameworks and business models, the most severe challenges to phasedown will come from enterprises that are profitable without policy support. While these now appear unlikely to be large, they will require vigilant policy oversight from early stages. Vigilance is especially needed for projects that link CDR with enhanced oil recovery, because weak or biased monitoring and emissions accounting could let these extend the life of fossil resources without actually achieving net removals. For removal projects that can only be viable with policy support, broad emissions-price policies, such as carbon taxes or cap-and-trade systems, do not appear to be good fits to motivate and manage a large-scale removal enterprise. These may help motivate early deployment but may be insufficient even at this stage due to large differences in removal methods' cost, scale limits, and development lead times. More narrowly targeted emissions-price policies, including those based on intensity standards, could surmount this difficulty, because they can target relevant actors and support internal emissions prices high enough to motivate early development of a broad range of removal methods. As removals grow large and net emissions go negative, however, any emissions price–based policies are likely to require major redesign, due to persistent wide disparities in marginal costs across multiple mitigation and removal approaches that cannot equilibrate due to various forms of unpriced constraints. Of the major approaches available to support removals, public procurement contracting appears most versatile for managing a large-scale removal enterprise of diverse methods and most amenable to managing eventual phasedown, although with some risk of regulatory capture.

Edward A. (Ted) Parson is Dan and Rae Emmett Professor of Environmental Law and faculty codirector of the Emmett Institute on Climate and Environment at UCLA. Parson studies international environmental law and policy as well as

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

the impacts and governance of disruptive technologies. He codirects the AI Pulse program at UCLA Law and organized the 2019 Summer Institute on AI and Society and the 2019 International Summer School on Geoengineering Governance. He holds degrees in physics from the University of Toronto and in management science from UBC and a PhD in public policy from Harvard. He formerly held faculty positions at the Harvard Kennedy School and the University of Michigan.

Holly Jean Buck is an environmental social scientist and geographer studying emerging technologies and environmental futures. She is currently a research fellow at UCLA's Institute of the Environment and Sustainability and the UCLA School of Law, and also an incoming assistant professor of environment and sustainability at the University at Buffalo, New York. She holds a PhD in development sociology from Cornell University.

References

Anderson, Kevin, and Glen Peters. 2016. The Trouble with Negative Emissions. *Science* 354 (6309): 182–183.

Baylis, Françoise. 2019. *Altered Inheritance*. Cambridge, MA: Harvard University Press.

Buck, Holly Jean, Laura Jane Martin, Oliver Geden, Peter Kareiva, Liz Koslov, Will Krantz, Ben Kravitz, et al. 2020. Evaluating the Efficacy and Equity of Environmental Stopgap Measures. *Nature Sustainability* 3: 499–504.

Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. 2015. Global Non-linear Effect of Temperature on Economic Production. *Nature* 527 (7577): 235–239.

Cairns, Rose C. 2014. Climate Geoengineering: Issues of Path-Dependence and Socio-technical Lock-In. *WIREs Climate Change* 5 (5): 649–661.

Carton, Wim. 2019. "Fixing" Climate Change by Mortgaging the Future: Negative Emissions, Spatiotemporal Fixes, and the Political Economy of Delay. *Antipode* 51 (3): 750–769.

Center for International Environmental Law. 2017. Smoke and Fumes: The Legal and Evidentiary Basis for Holding Big Oil Accountable for the Climate Crisis (Nov 2017). Center for International Environmental Law. Available at https://www.ciel.org/reports/smoke-and-fumes/, last accessed July 20, 2020.

Chavez, Anthony. 2018. "Using Renewable Portfolio Standards to Accelerate Development of Negative Emissions Technologies." *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3123125.

Dessler, Andrew E., and Edward A. Parson. 2019. *The Science and Politics of Global Climate Change: A Guide to the Debate*. 3rd ed. Cambridge, UK: Cambridge University Press.

Fuss, Sabine, Josep G. Canadell, Glen P. Peters, Massimo Tavoni, Robbie M. Andrew, Philippe Ciais, Robert B. Jackson, Chris D. Jones, Florian Kraxner, Nebosja Nakicenovic, Corinne Le Quéré, Michael R. Raupach, Ayyoob Sharifi, Pete Smith, and Yoshiki Yamagata. 2014. Betting on Negative Emissions. *Nature Climate Change* 4 (10): 850–853.

Fuss, Sabine, William F. Lamb, Max W. Callaghan, Jérôme Hilaire, Felix Creutzig, Thorben Amann, Tim Beringer, Wagner de Oliveira Garcia, Jens Hartmann, Tarun Khanna, Gunnar Luderer, Gregory F. Nemet, Joeri Rogelj, Pete Smith, José Luis Vicente Vicente,

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

Jennifer Wilcox, Maria del Mar Zamora Dominguez, and Jan C. Minx. 2018. Negative Emissions—Part 2: Costs, Potentials and Side Effects. *Environmental Research Letters* 13 (6): 063002.

Griscom, Bronson W., Justin Adams, Peter W. Ellis, Richard A. Houghton, Guy Lomax, Daniela A. Miteva, William H. Schlesinger, David Shoch, Juha V. Siikamäki, Pete Smith, Peter Woodbury, Chris Zganjar, Allen Blackman, João Campari, Richard T. Conant, Christopher Delgado, Patricia Elias, Trisha Gopalakrishna, Marisa R. Hamsik, Mario Herrero, Joseph Kiesecker, Emily Landis, Lars Laestadius, Sara M. Leavitt, Susan Minnemeyer, Stephen Polasky, Peter Potapov, Francis E. Putz, Jonathan Sanderman, Marcel Silvius, Eva Wollenberg, and Joseph Fargione. 2017. Natural Climate Solutions. *Proceedings of the National Academy of Sciences of the United States of America* 114 (44): 11645–11650.

Gunderson, Lance, and Garry Peterson. 2008. Practicing Adaptive Management in Complex Social-Ecological Systems. In *Complexity Theory for a Sustainable Future*, edited by J. Norberg and G. Cumming. New York, NY: Columbia University Press.

Hobbs, Richard J. 2017. *Novel Ecosystems: Can't We Just Pretend They're Not There?* Oxford, UK: Oxford University Press.

Honegger, Matthias, and David Reiner. 2017. The Political Economy of Negative Emissions Technologies: Consequences for International Policy Design. *Climate Policy* 18 (3): 306–321.

Intergovernmental Panel on Climate Change. 2018. *Global Warming of 1.5°C*. Intergovernmental Panel on Climate Change. Available at https://www.ipcc.ch/sr15/, last accessed July 23, 2020.

Jones, Andy, Jim M. Haywood, Kari Alterskjær, Olivier Boucher, Jason N. S. Cole, Charles L. Curry, Peter J. Irvine, Duoying Ji, Ben Kravitz, Jón Egill Kristjánsson, John C. Moore, Ulrike Niemeier, Alan Robock, Hauke Schmidt, Balwinder Singh, Simone Tilmes, Shingo Watanabe, and Jin-Ho Yoon. 2013. The Impact of Abrupt Suspension of Solar Radiation Management (Termination Effect) in Experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres* 118 (17): 9743–9752.

Jørgensen, Dolly. 2015. Ecological Restoration as Objective, Target, and Tool in International Biodiversity Policy. *Ecology and Society* 20 (4): 43.

Keith, David W., Geoffrey Holmes, David St. Angelo, and Kenton Heidel. 2018. A Process for Capturing CO_2 from the Atmosphere. *Joule* 2 (8): 1573–1594.

Keller, D. P., A. Lenton, V. Scott, N. E. Vaughan, N. Bauer, D. Ji, C. D. Jones, B. Kravitz, H. Muri, and K. Zickfeld. 2018. The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): Rationale and Experimental Protocol for CMIP6. *Geoscientific Model Development* 11 (3): 1133–1160.

Lacis, Andrew A., Gavin A. Schmidt, David Rind, and Reto A. Ruedy. 2010. Atmospheric CO_2: Principal Control Knob Governing Earth's Temperature. *Science* 330 (6002): 356–359.

Lander, Eric S., Françoise Baylis, Feng Zhang, Emmanuelle Charpentier, Paul Berg, Catherine Bourgain, Bärbel Friedrich, J. Keith Joung, Jinsong Li, David Liu, Luigi Naldini, Jing-Bao Nie, Renzong Qiu, Bettina Schoene-Seifert, Feng Shao, Sharon Terry, Wensheng Wei, and Ernst-Ludwig Winnacker. 2019. Adopt a Moratorium on Heritable Genome Editing. *Nature* 567 (7747): 165–168.

Ledbetter, James. 2011. *Unwarranted Influence: Dwight D. Eisenhower and the Military Industrial Complex*. New Haven, CT: Yale University Press.

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

Lenton, T. M. 2014. The Global Potential for Carbon Dioxide Removal. In *Geoengineering of the Climate System*, edited by R. E. Hester and R. M. Harrison, 52–79. Issues in Environmental Science and Technology Series 38. Cambridge, UK: Royal Society Chemistry.

Lenzi, Dominic. 2018. The Ethics of Negative Emissions. *Global Sustainability* 1: e7.

Levin, Kelly, Benjamin Cashore, Steven Bernstein, and Graeme Auld. 2012. Overcoming the Tragedy of Super Wicked Problems: Constraining Our Future Selves to Ameliorate Global Climate Change. *Policy Sciences* 45 (2): 123–152.

Lin, Albert. 2019. Carbon Dioxide Removal After Paris. *Ecology Law Quarterly* 45 (3): 533.

Luderer, Gunnar, Zoi Vrontisi, Christoph Bertram, Oreane Y. Edelenbosch, Robert C. Pietzcker, Joeri Rogelj, Harmen Sytze De Boer, Laurent Drouet, Johannes Emmerling, Oliver Fricko, Shinichiro Fujimori, Petr Havlík, Gokul Iyer, Kimon Keramidas, Alban Kitous, Michaja Pehl, Volker Krey, Keywan Riahi, Bert Saveyn, Massimo Tavoni, Detlef P. Van Vuuren, and Elmar Kriegler. 2018. Residual Fossil CO_2 Emissions in 1.5–2°C Pathways. *Nature Climate Change* 8 (7): 626–633.

Manchin, Joe. 2019. Text—S.1201—116th Congress (2019–2020): EFFECT Act of 2019. September 24. Available at https://www.congress.gov/bill/116th-congress/senate-bill/1201/text, last accessed July 20, 2020.

Markusson, Nils, Duncan McLaren, and David Tyfield. 2018. Towards a Cultural Political Economy of Mitigation Deterrence by Negative Emissions Technologies (NETs). *Global Sustainability* 1: e10.

Mathesius, Sabine, Matthias Hofmann, Ken Caldeira, and Hans Joachim Schellnhuber. 2015. Long-Term Response of Oceans to CO_2 Removal from the Atmosphere. *Nature Climate Change* 5 (12): 1107–1113.

Minx, Jan C., William F. Lamb, Max W. Callaghan, Sabine Fuss, Jérôme Hilaire, Felix Creutzig, Thorben Amann, Tim Beringer, Wagner de Oliveira Garcia, Jens Hartmann, Tarun Khanna, Dominic Lenzi, Gunnar Luderer, Gregory F. Nemet, Joeri Rogelj, Pete Smith, Jose Luis Vicente Vicente, Jennifer Wilcox, and Maria del Mar Zamora Dominguez. 2018. Negative Emissions—Part 1: Research Landscape and Synthesis. *Environmental Research Letters* 13 (6): 063001.

National Research Council. 2015a. *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. Washington, DC: National Academies Press.

National Research Council. 2015b. *Climate Intervention: Reflecting Sunlight to Cool Earth*. Washington, DC: National Academies Press.

National Research Council. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: National Academies Press.

Nemet, Gregory F., Max W. Callaghan, Felix Creutzig, Sabine Fuss, Jens Hartmann, Jérôme Hilaire, William F. Lamb, Jan C. Minx, Sophia Rogers, and Pete Smith. 2018. Negative Emissions—Part 3: Innovation and Upscaling. *Environmental Research Letters* 13 (6): 063003.

Obersteiner, Michael, Johannes Bednar, Fabian Wagner, Thomas Gasser, Philippe Ciais, Nicklas Forsell, Stefan Frank, Petr Havlik, Hugo Valin, Ivan A. Janssens, Josep Peñuelas, and Guido Schmidt-Traub. 2018. How to Spend a Dwindling Greenhouse Gas Budget. *Nature Climate Change* 8 (1): 7–10.

Oreskes, Naomi, and Erik M. Conway. 2010. *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming*. London, UK: Bloomsbury Press.

Parker, Andy, and Peter J. Irvine. 2018. The Risk of Termination Shock from Solar Geoengineering. *Earth's Future* 6 (3): 456–467.

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

Parson, Edward A. 2015. Focus Less on Collective Action, More on Delayed Benefits and Concentrated Opponents. June. Available at https://www.cigionline.org/publications/focus-less-collective-action-more-delayed-benefits-and-concentrated-opponents, last accessed July 20, 2020.

Parson, Edward A. 2017. Climate Policymakers and Assessments Must Get Serious About Climate Engineering. *Proceedings of the National Academy of Sciences of the United States of America* 114 (35): 9227–9230.

Parson, Edward A., Julia Forgie, Jesse Lueders, and Sean B. Hecht. 2018. Controlling Greenhouse Gas Emissions from Transport Fuels: The Performance and Prospect of California's Low Carbon Fuel Standard. Pritzker Brief 10. Emmett Institute on Climate Change & the Environment. Available at https://law.ucla.edu/news/controlling-greenhouse-gas-emissions-transport-fuels, last accessed July 23, 2020.

Preston, Christopher J. 2016. Climate Engineering and the Cessation Requirement: The Ethics of a Life-Cycle. *Environmental Values* 25 (1): 91–107.

Rau, Greg H. 2019. The Race to Remove CO_2 Needs More Contestants. *Nature Climate Change* 9: 256.

Rau, Greg H., Heather D. Willauer, and Zhiyong Jason Ren. 2018. The Global Potential for Converting Renewable Electricity to Negative-CO_2-Emissions Hydrogen. *Nature Climate Change* 8 (7): 621–625.

Renforth, P., P. A. E. Pogge von Strandmann, and G. M. Henderson. 2015. The Dissolution of Olivine Added to Soil: Implications for Enhanced Weathering. *Applied Geochemistry* 61: 109–118.

Rhodium Group. 2019. Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology. Available at https://rhg.com/research/capturing-leadership-policies-for-the-us-to-advance-direct-air-capture-technology/, last accessed July 20, 2020.

Rogge, Karoline S., and Phil Johnstone. 2017. Exploring the Role of Phase-Out Policies for Low-Carbon Energy Transitions: The Case of the German Energiewende. *Energy Research and Social Science* 33 (November): 128–137.

Royal Society and Royal Academy of Engineering. 2018. *Greenhouse Gas Removal*. Available at https://royalsociety.org/topics-policy/projects/greenhouse-gas-removal/, last accessed July 23, 2020.

Sanchez, Daniel L., and Daniel M. Kammen. 2016. A Commercialization Strategy for Carbon-Negative Energy. *Nature Energy* 1 (1): 1–4.

Sarewitz, Daniel, and Richard Nelson. 2008. Three Rules for Technological Fixes. *Nature* 456 (7224): 871–872.

Schultz, Lisen, Carl Folke, Henrik Österblom, and Per Olsson. 2015. Adaptive Governance, Ecosystem Management, and Natural Capital. *Proceedings of the National Academy of Sciences of the United States of America* 112 (24): 7369–7374.

Seto, Karen C., Steven J. Davis, Ronald B. Mitchell, Eleanor C. Stokes, Gregory Unruh, and Diana Ürge-Vorsatz. 2016. Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources* 41 (1): 425–452.

Shue, Henry. 2017. Climate Dreaming: Negative Emissions, Risk Transfer, and Irreversibility. *Journal of Human Rights and the Environment* 8 (2): 203–216.

Smith, P., S. J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato, Robert B. Jackson, Annette Cowie, Elmar Kriegler, Detlef P. van Vuuren, Joeri Rogelj, Philippe Ciais, Jennifer Milne, Josep G. Canadell, David McCollum, Glen Peters, Robbie Andrew, Volker Krey, Gyami Shrestha, Pierre Friedlingstein, Thomas Gasser, Arnulf Grübler,

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021

Wolfgang K. Heidug, Matthias Jonas, Chris D. Jones, Florian Kraxner, Emma Littleton, Jason Lowe, José Roberto Moreira, Nebojsa Nakicenovic, Michael Obersteiner, Anand Patwardhan, Mathis Rogner, Ed Rubin, Ayyoob Sharifi, Asbjørn Torvanger, Yoshiki Yamagata, Jae Edmonds, and Cho Yongsung. 2016. Biophysical and Economic Limits to Negative CO_2 Emissions. *Nature Climate Change* 6 (January): 42–50.

Stegmaier, Peter, Stefan Kuhlmann, and Vincent R. Visser. 2014. The Discontinuation of Socio-technical Systems as a Governance Problem. In *The Governance of Socio-technical Systems*, edited by Susana Borrás and Jakob Edler, 111–131. Cheltenham, UK: Edward Elgar.

Tanzer, Samantha Eleanor, and Andrea Ramírez. 2019. When Are Negative Emissions Negative Emissions? *Energy and Environmental Science* 12 (4): 1210–1218.

Trisos, Christopher H., Giuseppe Amatulli, Jessica Gurevitch, Alan Robock, Lili Xia, and Brian Zambri. 2018. Potentially Dangerous Consequences for Biodiversity of Solar Geoengineering Implementation and Termination. *Nature Ecology and Evolution* 2 (3): 475–482.

Turnheim, Bruno, and Frank W. Geels. 2013. The Destabilisation of Existing Regimes: Confronting a Multi-dimensional Framework with a Case Study of the British Coal Industry (1913–1967). *Research Policy* 42 (10): 1749–1767.

van Vuuren, Detlef P., Elke Stehfest, David E. H. J. Gernaat, Maarten van den Berg, David L. Bijl, Harmen Sytze de Boer, Vassilis Daioglou, Jonathan C. Doelman, Oreane Y. Edelenbosch, Mathijs Harmsen, Andries F. Hof, and Mariësse A. E. van Sluisveld. 2018. Alternative Pathways to the 1.5 °C Target Reduce the Need for Negative Emission Technologies. *Nature Climate Change* 8 (April): 391–397.

Vaughan, N. E., and C. Gough. 2016. Expert Assessment Concludes Negative Emissions Scenarios May Not Deliver. *Environmental Research Letters* 11 (9): 7.

Vergragt, Philip J., Nils Markusson, and Henrik Karlsson. 2011. Carbon Capture and Storage, Bio-energy with Carbon Capture and Storage, and the Escape from the Fossil-Fuel Lock-In. *Global Environmental Change* 21 (2): 282–292.

Downloaded from http://www.mitpressjournals.org/doi/pdf/10.1162/glep_a_00575 by guest on 31 August 2021