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Carbon Dioxide Removal after Paris

Albert C. Lin*

Notwithstanding adoption of the Paris Agreement on climate change, mitigation of greenhouse gas emissions appears unlikely to achieve the stated goal of limiting the mean global temperature increase to 2°C. Under many scenarios, achieving this goal would require not only vigorous mitigation efforts, but also the deployment of carbon dioxide removal technologies or solar geoengineering. While serious consideration of solar geoengineering remains fraught with peril, the use of carbon dioxide removal to remove carbon dioxide from the atmosphere and store it elsewhere appears increasingly likely. Carbon dioxide removal techniques generally would have to be undertaken on a massive scale to be effective. However, the techniques are not ready for deployment, and their widespread use would impact land use, biodiversity, food security, water availability, and other resources.

Such impacts demand greater attention to managing carbon dioxide removal efforts and their effects. The Paris Agreement does not directly mention carbon dioxide removal, however, and relatively little attention has been directed toward carbon dioxide removal governance thus far. This Article explores key issues of carbon dioxide removal governance, such as promoting the generation of information, mainstreaming carbon dioxide removal into public and policy discussions, and furthering carbon dioxide removal development while avoiding lock-in of suboptimal technologies.

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INTRODUCTION

Historically, climate change response efforts have emphasized mitigation—directly reducing greenhouse gas (GHG) emissions by, for example, increasing energy efficiency or substituting renewable energy for fossil fuels. The 2015 Paris Agreement on climate change continues this emphasis on mitigation while offering individual countries broad flexibility regarding the specific measures they must undertake. Through the international community’s collective efforts, the Paris Agreement aims to limit the mean global temperature increase to 2°C (“2C goal”) and to pursue an even more ambitious target of avoiding a 1.5°C temperature increase.

These goals will be difficult to achieve. Anthropogenic GHG emissions caused average global temperatures to rise 0.8°C between 1880 and 2012, and the cumulative GHGs already released into the atmosphere have locked in an

estimated further temperature increase of 0.3°C.¹ Currently, the world emits forty gigatons of carbon dioxide equivalent (Gt CO₂) each year, and emissions are expected to increase until 2030 under the national emission pledges submitted pursuant to the Paris Agreement.² As a result, mitigation alone is unlikely to achieve the 2C goal. Indeed, the climate response models that underlay the Paris talks assume heavy reliance on carbon dioxide removal (CDR) techniques—in addition to mitigation—in order to achieve the 2C goal.³ In contrast to mitigation, which strives to prevent carbon dioxide (CO₂) and other GHGs from entering the atmosphere in the first instance, CDR encompasses a variety of proposed methods to remove CO₂ already present in the atmosphere.

Troublingly, the global community has paid little attention to the groundwork needed to deploy CDR on the immense scale the 2C goal assumes. A number of scientists have recognized CDR's pivotal role under Paris, but few analysts have contemplated how to establish the policy and legal foundations for CDR. Beyond academia, neither the international community nor individual nations have explicitly considered whether they should deploy CDR on a widespread basis in response to climate change. The general public, moreover, is largely unaware of the issue.

This Article explains why policymakers must turn their attention to CDR governance and explores laws and policies for CDR that could be essential to meeting the Paris goals. In urging immediate attention to CDR, I do not mean to argue that the global community necessarily *should* deploy CDR broadly in response to climate change. CDR technologies are far from ready for deployment, and wholesale commitment to CDR is premature. Furthermore, each CDR technique has serious limitations, and widespread deployment likely would raise critical concerns regarding ecological harms, food security, and intragenerational and intergenerational equity.⁴ At the same time, however, mitigation without CDR will not be enough. Ignoring the fundamental assumptions underlying the Paris goals might well ensure a failure to meet those goals.⁵ The international community should flesh out these assumptions, test their validity, and publicly debate CDR's role in climate change policy.

1. See U.S. GLOBAL CHANGE RESEARCH PROGRAM, CLIMATE CHANGE IMPACTS IN THE UNITED STATES: THE THIRD NATIONAL CLIMATE ASSESSMENT 23, 25 (2014).

2. See Kevin Anderson & Glen Peters, *The Trouble with Negative Emissions*, 354 SCIENCE 182, 182 (2016). Full implementation of such pledges and policies of similar strength are projected to lead to a 2.7° C temperature increase. See EUROPEAN ACADEMIES SCIENCE ADVISORY COUNCIL, NEGATIVE EMISSION TECHNOLOGIES: WHAT ROLE IN MEETING PARIS AGREEMENT TARGETS? 3 (2018) [hereinafter EASAC].

3. See Anderson & Peters, *supra* note 2, at 182.

4. Intragenerational equity refers to equitable access to resources among different peoples and nations, whereas intergenerational equity refers to access to a level of planetary health no worse than previous generations. See Edith Brown Weiss, *Our Rights and Obligations to Future Generations for the Environment*, 84 AM. J. INT'L L. 198, 200–01 (1990).

5. Cf. EASAC, *supra* note 2, at 1 (noting that despite the limitations of CDR, “halting increases in the concentration of GHGs in the atmosphere remains a race against time, and humanity will require all possible tools to limit warming within Paris Agreement targets”).

Part I of this Article offers an overview of proposed CDR techniques and considers their technical feasibility, potential efficacy, and social acceptability. Part II situates CDR within the international climate change regime. While the Paris Agreement does not explicitly mention CDR, the agreement's core objective assumes significant reliance on CDR. Part III considers efforts to stimulate technological development and adoption in areas analogous to CDR. Experiences in encouraging better forest carbon management, developing renewable fuels, and promoting carbon capture and storage technologies suggest useful lessons for approaching CDR policy. Part IV explains why CDR deserves the international community's prompt attention, notwithstanding the relatively immature state of CDR technologies. The Article concludes with recommendations on how to proceed and proposes specific elements of a CDR policy.

I. WHAT IS CARBON DIOXIDE REMOVAL?

A. *An Introduction to CDR Techniques*

CDR, or negative emission technologies, encompasses various proposed techniques for removing carbon dioxide from the atmosphere and storing it in the earth or oceans.⁶ While oceans, forests, and the land naturally remove some CO₂ from the atmosphere as part of the carbon cycle, CDR specifically refers to human activities aimed deliberately at CO₂ removal. CDR techniques include bioenergy with carbon capture and storage (BECCS), direct air capture and storage (DACs), biochar, enhanced weathering, and ocean fertilization.⁷ Afforestation and similar land management strategies are sometimes classified as CDR as well, although they have been integrated into the international climate change regime as a type of mitigation.⁸

CDR is commonly envisioned as a mechanism for slowing and eventually halting the rise in atmospheric GHG concentrations.⁹ To be sure, removing CO₂ from the atmosphere is generally more expensive than not emitting it in the first place.¹⁰ However, CDR could serve as a less costly alternative to reducing those

6. See THE ROYAL SOCIETY, *GEOENGINEERING THE CLIMATE: SCIENCE, GOVERNANCE, AND UNCERTAINTY* 9 (2009). Negative emission technologies is a potentially broader term that includes techniques to remove GHGs other than CO₂. The possibility of developing such techniques has received far less attention, however. See SECRETARIAT OF THE CONVENTION ON BIOLOGICAL DIVERSITY, *CBD TECHNICAL SERIES NO. 84, UPDATE ON CLIMATE GEOENGINEERING IN RELATION TO THE CONVENTION ON BIOLOGICAL DIVERSITY: POTENTIAL IMPACTS AND REGULATORY FRAMEWORK* at 68 (2016) [hereinafter *CBD 84*].

7. See NATIONAL RESEARCH COUNCIL, *CLIMATE INTERVENTION: CARBON DIOXIDE REMOVAL AND RELIABLE SEQUESTRATION 2* (2015) [hereinafter *NAS CDR*].

8. See James Meadowcroft, *Exploring Negative Territory: Carbon Dioxide Removal and Climate Policy Initiatives*, 118 *CLIMATIC CHANGE* 137, 139 (2013); see also *infra* Part III.A.

9. See *id.* at 140–41; PARLIAMENTARY OFFICE OF SCIENCE & TECHNOLOGY (UK), *GREENHOUSE GAS REMOVAL*, POSTNOTE NO. 549 (2017).

10. See Sabine Fuss et al., *Betting on Negative Emissions*, 4 *NATURE CLIMATE CHANGE* 850, 851 (2014).

GHG emissions that are difficult or impossible to eliminate, such as emissions from aircraft.¹¹ Alternatively, or additionally, CDR could also be used to reduce atmospheric GHG concentrations that have exceeded safe levels.¹² Relying on CDR to address this second, “overshoot,” scenario rests on the untested assumption that climatic changes occurring during the overshoot period—such as loss of sea or land ice, species extinction, or ocean acidification—are reversible.¹³

Apart from their potential to remove CO₂ from the atmosphere, CDR approaches vary widely.¹⁴ They use different mechanisms to capture and store carbon, operate over different time scales, have different costs and benefits, and are subject to different constraints.¹⁵ Nonetheless, all methods of CDR are slow-acting; as a result of thermal inertia, global temperatures will continue to rise for decades even after such methods are applied.¹⁶ In addition, most CDR technologies are at an early stage of development and—having been the subject of little if any field research—are not ready to be commercialized.¹⁷ Even if a particular technology were to achieve commercial viability, an extended period of time would be necessary for it to achieve a meaningful scale.¹⁸

The following discussion introduces a number of widely discussed CDR technologies. BECCS, which many climate change researchers have incorporated into their modeling efforts, is considered in greatest detail, but other CDR technologies also could prove to be important.

1. BECCS

Bioenergy with carbon capture and storage “is by far the most prominent” CDR option that climate modelers have considered in sketching out pathways to

11. See Meadowcroft, *supra* note 8, at 141; NAS CDR, *supra* note 7, at 88; Fuss et al., *supra* note 10, at 851 (noting that “some of the non-CO₂ emissions . . . will be very difficult to mitigate completely, as will some CO₂ emissions from industry and transportation”).

12. See Meadowcroft, *supra* note 8, at 140.

13. See Sabine Fuss et al., *Research Priorities for Negative Emissions*, 11 ENVTL. RESEARCH LETTERS 115007, 7 (2016); Christopher B. Field & Katharine J. Mach, *Rightsizing Carbon Dioxide Removal*, 356 SCIENCE 706, 707 (2017); Sivan Kartha & Kate Dooley, *The Risks of Relying on Tomorrow’s “Negative Emissions” to Guide Today’s Mitigation Action* 5, 9 (Stockholm Env’t Inst. Working Paper No. 08, 2016).

14. See Meadowcroft, *supra* note 8, at 138.

15. See *id.* at 138–39.

16. See INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS: WORKING GROUP I CONTRIBUTION TO THE FIFTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 550 (2013) [hereinafter WG1AR5]; T.M.L. Wigley, *The Climate Change Commitment*, 307 SCIENCE 1766, 1769 (2005) (exploring continued temperature and sea level rise under the assumption that respective concentrations of atmospheric gases remain constant).

17. See Duncan McLaren, *A Comparative Global Assessment of Potential Negative Emission Technologies*, 90 PROCESS SAFETY & ENVTL. PROT. 489, 491 (2012); Guy Lomax et al., *Reframing the Policy Approach to Greenhouse Gas Removal Technologies*, 78 ENERGY POLICY 125, 126 (2015).

18. See Fuss et al., *Betting*, *supra* note 10, at 852.

achieve the 2C goal.¹⁹ BECCS has received the lion's share of attention largely because it provides something of economic value—energy—to partly offset the high costs of removing CO₂ from the atmosphere.²⁰ BECCS begins with the cultivation of bioenergy crops, which remove carbon from the air during photosynthesis.²¹ Burning the resultant biomass at power stations yields energy as well as carbon dioxide, which is captured, compressed, and stored in liquid form in geologic reservoirs or the deep ocean.²² The ability to remove CO₂ from the atmosphere through BECCS is constrained primarily by the availability of land for growing biomass, and less so by carbon storage capacity. Estimates suggest that the oceans or geologic reservoirs could store thousands of Gt CO₂,²³ whereas land constraints may limit carbon removal by BECCS to no more than 2.4 to 10 Gt CO₂ per year.²⁴

Though sometimes described as the “most mature” of all CDR approaches,²⁵ BECCS is far from ready for large-scale deployment. Carbon capture and storage (CCS), a critical component of BECCS, has been the subject of extensive development efforts but has yet to achieve commercial scale.²⁶ CCS is costly, and establishing the infrastructure for capturing, transporting, and storing carbon faces stiff challenges.²⁷ BECCS is even further from commercial deployment than CCS alone. The first industrial scale BECCS project devoted to carbon storage—a facility integrated with a corn ethanol plant in Illinois—only began operations in April 2017.²⁸ This project is a potentially important development, but does not represent a prototype for effectively removing CO₂ from the atmosphere. Because the project is part of an ethanol facility, it captures only a small fraction of the carbon content of the original feedstock; most of the

19. See C. Gough & N.E. Vaughan, *Synthesizing Existing Knowledge on the Feasibility of BECCS* 5 (2015) [hereinafter WPD 1a]; N.E. Vaughan & C. Gough, *Synthesizing Existing Knowledge on the Feasibility of BECCS: Workshop Report* 26 (2015) [hereinafter WPD 1b] (recounting workshop participants' characterizations of BECCS as “the silver bullet” and “the least expensive fantasy technology”).

20. See Anderson & Peters, *supra* note 2, at 183.

21. See Phil Williamson, *Scrutinize CO₂ Removal Methods*, 530 NATURE 153, 153–54 (2016).

22. See Naomi Vaughan & Timothy M. Lenton, *A Review of Climate Geoengineering Proposals*, 109 CLIMATIC CHANGE 745, 752, 760 (2011) (noting ecological concerns associated with ocean storage). The alternative use of biomass to produce biofuels offers little carbon dioxide removal benefit once the biofuels are combusted. *Id.* at 751.

23. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2014: MITIGATION OF CLIMATE CHANGE: WORKING GROUP III CONTRIBUTION TO THE FIFTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 485 (2014) [hereinafter WG3AR5].

24. See McLaren, *supra* note 17, at 494.

25. See Gough & Vaughan, WPD 1a, *supra* note 19, at 20.

26. See *infra* text accompanying notes 231–236.

27. See Gough & Vaughan, WPD 1a, *supra* note 19, at 16–17; POSTNOTE, *supra* note 9, at 3. Part III.C discusses CCS in further detail.

28. See Chris Mooney, *The Quest to Capture and Store Carbon—and Slow Climate Change—Just Reached a New Milestone*, WASH. POST (Apr. 10, 2017), https://www.washingtonpost.com/news/energy-environment/wp/2017/04/10/the-quest-to-capture-and-store-carbon-and-slow-climate-change-just-reached-a-new-milestone/?noredirect=on&utm_term=.2e8316695b1f (discussing launch of facility expected to store over five million tons of CO₂ over a five-year period).

carbon escapes into the air when the ethanol is burned as fuel.²⁹ Moreover, most scenarios that envision widespread BECCS deployment assume the use of agricultural and forestry waste, switchgrass, or other second-generation bioenergy crops as a feedstock, rather than corn or similar crops that require more substantial fossil energy inputs and management effort.³⁰

Deploying BECCS at a scale sufficient to slow climate change would compete with other land uses and “vastly accelerate the loss of primary forest and natural grassland.”³¹ One estimate suggests that approximately one-third of Earth’s arable land would need to be devoted to planting crops for the purpose of carbon removal in order to limit global temperature rise to 2°C, assuming mitigation efforts envisioned under the Paris Agreement.³² Cultivation of bioenergy crops on this scale would not occur solely on marginal land; rather, it would likely displace food and fiber production.³³ The specific effects of bioenergy crop cultivation on livelihoods would depend on social conditions as well as physical constraints.³⁴ Scaled-up BECCS would require efforts from many nations, including regions with poor and vulnerable populations, and could adversely impact food security, water availability, biodiversity, and indigenous peoples’ rights and livelihoods.³⁵

In addition, the climate change benefits of BECCS may fall short of projections. Clearing land and applying fertilizer in the course of growing bioenergy crops would release CO₂ and other GHGs.³⁶ Anticipated bioenergy crop yields may decline as water becomes scarcer, weather more severe, precipitation more variable, and pests more abundant.³⁷ And cultivation of bioenergy crops could decrease Earth’s reflectivity, or albedo, thereby contributing to additional warming.³⁸

29. See Gough & Vaughan, WPD 1a, *supra* note 19, at 22.

30. See *id.* at 10.

31. Williamson, *supra* note 21, at 154; see WG1AR5, *supra* note 16, at 547; Lena R. Boysen et al., *Trade-Offs for Food Production, Nature Conservation and Climate Limit the Terrestrial Carbon Dioxide Removal Potential*, 23 GLOB. CHANGE BIOLOGY 4303, 4313 (2017) (“We conclude that land availability for [terrestrial CDR] is very limited if constrained by the simultaneous needs for food production (‘food first’) as well as nature conservation (‘conservation first’) and local climate protection through albedo changes (‘climate first’).”).

32. See Williamson, *supra* note 21, at 154. This figure assumes the planting of crops so as to remove 600 Gt CO₂ over this century, the median estimate of how much CO₂ would need to be removed. See *id.*

33. See Holly Buck, *Rapid Scale-Up of Negative Emission Technologies: Social Barriers and Social Implications*, 139 CLIMATIC CHANGE 155, 158 (2016).

34. See WG3AR5, *supra* note 23, at 835 (noting that “total impact [of bioenergy crop cultivation] on livelihood and distributional consequences depends on global market factors, impacting income and income-related food security, and site-specific factors such as land tenure and social dimensions”).

35. See Kartha & Dooley, *supra* note 13, at 7; Gough & Vaughan, WPD 1a, *supra* note 19, at 26, 31; William C.G. Burns, *Human Rights Dimensions of Bioenergy With Carbon Capture and Storage: A Framework for Climate Justice in the Realm of Climate Geoengineering*, in CLIMATE JUSTICE: CASE STUDIES IN GLOBAL AND REGIONAL GOVERNANCE CHALLENGES 149, 160–62 (Randall Abate ed., 2016).

36. See Williamson, *supra* note 21, at 154; Lena R. Boysen et al., *The Limits to Global-Warming Mitigation by Terrestrial Carbon Removal*, 5 EARTH’S FUTURE 463, 470 (2017).

37. See POSTNOTE, *supra* note 9, at 3; Williamson, *supra* note 21, at 154.

38. See Boysen et al., *supra* note 31, at 4308.

2. DACS

Direct air capture uses chemical processes to extract CO₂ from the air.³⁹ The material used to extract the CO₂, or substrate, must then be regenerated, and the CO₂ released in the regeneration process is then stored in the earth or ocean.⁴⁰ In contrast to BECCS, DACS is not limited by land availability, and thus offers a higher potential CO₂ capture capacity, perhaps exceeding ten Gt CO₂ per year.⁴¹ DACS also offers greater locational flexibility, as facilities could be placed close to sequestration sites or renewable energy sources that would power the extraction process.⁴² Despite these advantages, DACS has comparatively high costs. The estimated cost of removing carbon via DACS exceeds \$250 per ton of CO₂ and could remain prohibitively expensive.⁴³ DACS is costly because it requires a great deal of energy to capture CO₂ from the ambient air, where its concentration is 0.04 percent, a small fraction of its concentration in smokestacks of power plants or industrial facilities.⁴⁴ Put another way, capturing and sequestering CO₂ from coal- or gas-fired power plants is much easier and cheaper than using DACS to achieve the same objective.⁴⁵ Furthermore, while using renewable energy to power DACS would reduce its carbon footprint, doing so would likely require significant amounts of land.⁴⁶

3. Other Techniques

Several CDR techniques propose to enhance carbon sinks on land or in the ocean. These include afforestation and reforestation,⁴⁷ biochar, enhanced weathering, and ocean fertilization. Unlike other CDR techniques, afforestation and reforestation are already feasible.⁴⁸ However, these methods offer only short-term carbon storage, and converting grasslands to forest may release carbon stored in the soil.⁴⁹ Furthermore, afforestation could exacerbate warming by reducing albedo, particularly in regions accustomed to seasonal snow cover.⁵⁰ Such concerns, along with afforestation's limited potential to store large amounts

39. See Vaughan & Lenton, *supra* note 22, at 758–59; NAS CDR, *supra* note 7, at 56.

40. See NAS CDR, *supra* note 7, at 56–57.

41. See Vaughan & Lenton, *supra* note 22, at 759; McLaren, *supra* note 17, at 494.

42. See NAS CDR, *supra* note 7, at 61.

43. See Vaughan & Lenton, *supra* note 22, at 759; McLaren, *supra* note 17, at 494 fig.2, 495. DACS could become economically competitive with BECCS if the full social and ecological costs of broad-scale BECCS are accounted for. See Jasmin Kemper, *Biomass and Carbon Dioxide Capture and Storage: A Review*, 40 INT'L J. GREENHOUSE GAS CONTROL 401, 415 (2015).

44. See THE ROYAL SOCIETY, *supra* note 6, at 15.

45. See NAS CDR, *supra* note 7, at 58.

46. See Buck, *supra* note 33, at 157.

47. Afforestation refers to the restoration of forest on land that has been deforested for at least fifty years, whereas reforestation refers to the restoration of forest on recently deforested land. See NAS CDR, *supra* note 7, at 28.

48. See McLaren, *supra* note 17, at 492.

49. See Vaughan & Lenton, *supra* note 22, at 751; WG1AR5, *supra* note 16, at 547–49.

50. See WG1AR5, *supra* note 16, at 551. By contrast, afforestation in the tropics could generate a net cooling effect as a result of increased rates of evapotranspiration. *Id.*

of carbon, render it no more than a complimentary tool in addressing climate change.

Biochar involves burning biomass in the absence of oxygen to produce charcoal, which when plowed into the soil simultaneously enhances its nutrient content and stores carbon.⁵¹ As with BECCS, scaled-up deployment of biochar would require growing substantial quantities of biomass over large land areas.⁵² Although scientists have not determined the maximum amount of biochar that could be incorporated into the Earth's soils, the technique's capacity to store carbon appears to be less than that of BECCS.⁵³ Furthermore, adding biochar to the soil decreases albedo and thus would have a warming effect.⁵⁴

Enhanced weathering involves adding ground-up silicate rocks to soils or the ocean in order to trigger chemical reactions that would absorb CO₂ from the atmosphere.⁵⁵ One estimate suggests the technique could remove up to four Gt CO₂ per year from the atmosphere, but development of the technique thus far has been limited to lab-scale experiments.⁵⁶ Widespread deployment of enhanced weathering would have tremendous environmental impacts. Mining, processing, and applying huge quantities of rock would have environmental consequences comparable to, if not exceeding, those associated with current coal mining operations and cement production.⁵⁷ Some enhanced weathering techniques would also require large volumes of seawater.⁵⁸ Deploying the technique in the oceans could offer a side benefit of counteracting ocean acidification, as adding silicate rocks would increase the alkalinity of marine waters.⁵⁹ However, much concern—and uncertainty—surround these and other possible ecological consequences of enhanced weathering.⁶⁰

Finally, ocean fertilization calls for adding iron or other nutrients to the oceans to stimulate biological productivity.⁶¹ In theory, increased microorganism populations would extract carbon from the air and transport the carbon to the ocean depths when they die.⁶² However, ocean fertilization would alter ocean chemistry and marine ecosystems, and also could disrupt food webs, reduce oxygen availability, and trigger harmful algal blooms.⁶³ Furthermore,

51. See THE ROYAL SOCIETY, *supra* note 6, at 11–12.

52. See *id.* at 12.

53. See Vaughan & Lenton, *supra* note 22, at 752; THE ROYAL SOCIETY, *supra* note 6, at 12–13; McLaren, *supra* note 17, at 494.

54. See Vaughan & Lenton, *supra* note 22, at 752.

55. See Williamson, *supra* note 21, at 154.

56. See NAS CDR, *supra* note 7, at 47.

57. See Williamson, *supra* note 21, at 155; NAS CDR, *supra* note 7, at 41–42; THE ROYAL SOCIETY, *supra* note 6, at 14.

58. See NAS CDR, *supra* note 7, at 42.

59. See *id.* at 43; THE ROYAL SOCIETY, *supra* note 6, at 14.

60. See NAS CDR, *supra* note 7, at 43; WG1AR5, *supra* note 16, at 551.

61. See Vaughan & Lenton, *supra* note 22, at 753, 755–56.

62. See *id.*

63. See NAS CDR, *supra* note 7, at 51–52; see also INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2014 IMPACTS, ADAPTATION, AND VULNERABILITY: WORKING GROUP II

ocean fertilization's capacity to remove carbon from the atmosphere appears quite limited.⁶⁴ Field research thus far suggests that the technique would not be effective at sequestering carbon in the deep oceans, as much of the carbon is likely to return to the atmosphere when microorganisms decay.⁶⁵ Ocean fertilization's expected environmental impacts and limited efficacy, combined with the difficulty of verifying any carbon benefits, have led to its characterization as "an immature CDR technology with high technical and environmental risk."⁶⁶

B. Would CDR Actually Reduce Atmospheric GHG Levels?

As the above discussion suggests, CDR technologies offer neither a quick nor easy fix for climate change. CDR is expensive and slow acting. In order to significantly reduce atmospheric CO₂ levels, CDR technologies would have to be deployed at large scale for extended periods of time.⁶⁷ At such a scale, CDR techniques could have troubling consequences for society and the environment. Beyond these concerns, a critical question is whether CDR actually would reduce atmospheric GHG concentrations. For a number of reasons, the net reduction in atmospheric carbon from deploying CDR will be less than the gross amount of carbon a particular technique removes.

As an initial matter, the process of removing and storing atmospheric carbon itself will generate GHG emissions. A full carbon accounting for BECCS, for example, would include emissions associated with soil disturbance, land-use change, fertilizer use, biomass transportation, CO₂ compression, and underground injection.⁶⁸ In addition, the technology only sequesters a proportion of the carbon contained in the initial biomass, depending on the processes used in handling, treating, and burning the biomass.⁶⁹ Similarly, life cycle analyses of DACS should account for carbon released in the energy-intensive processes of carbon capture and substrate regeneration, in addition to emissions associated with storing carbon in the ground.⁷⁰ CDR techniques that enhance natural carbon sinks also would generate GHGs: enhanced weathering would require significant amounts of energy to mine, crush, and transport materials;⁷¹ ocean fertilization

CONTRIBUTION TO THE FIFTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 454 (2014); WG1AR5, *supra* note 16, at 551.

64. See McLaren, *supra* note 17, at 494.

65. See Vaughan & Lenton, *supra* note 22, at 756.

66. NAS CDR, *supra* note 7, at 53.

67. See WG1AR5, *supra* note 16, at 546.

68. See NAS CDR, *supra* note 7, at 54–55; WG3AR5, *supra* note 23, at 835; WG1AR5, *supra* note 16, at 551. Life cycle analyses to date suggest that BECCS could lead to both carbon positive and negative results, depending on specific conditions of deployment. See Mathilde Fajardy & Niall Mac Dowell, *Can BECCS Deliver Sustainable and Resource Efficient Negative Emissions?*, 10 ENERGY & ENVTL. SCI. 1389, 1389 (2017).

69. See Gough & Vaughan, WPD 1a, *supra* note 19, at 25.

70. See POSTNOTE, *supra* note 9, at 3.

71. See WG3AR5, *supra* note 23, at 485.

could trigger releases of methane and nitrous oxide—GHGs that have a much greater warming effect than CO₂;⁷² and use of nitrogen fertilizers in afforestation projects could increase nitrous oxide release.⁷³

Furthermore, releases of CO₂ from natural carbon sinks will partially offset removals of CO₂ from the atmosphere.⁷⁴ Namely, the ocean and land have served as significant climate change buffers, absorbing much of the atmospheric CO₂ added by human activity.⁷⁵ Removing a significant quantity of CO₂ from the atmosphere would reverse the direction of the buffering activity, causing CO₂ to outgas from the land and oceans back into the atmosphere.⁷⁶ Calculations of CDR effectiveness should account for these rebound effects, which could offset half of the CO₂ that CDR efforts remove.⁷⁷

CDR techniques also raise questions regarding the permanence of carbon storage in varying ways. With respect to afforestation, for example, fires, droughts, pests, and disease could undermine carbon storage efforts.⁷⁸ Biochar's effectiveness in securing long-term carbon removal is highly uncertain and may depend on the nature of the feedstock, the biochar production process, and subsequent environmental conditions.⁷⁹ Even relatively permanent storage techniques face concerns. CO₂ stored in geological reservoirs might leak out, though the risk of leakage could be reduced by storing CO₂ as a liquid beneath the oceans or reacting CO₂ with certain types of rock.⁸⁰ All of the foregoing concerns—additional GHG emissions, offsetting releases, and impermanent storage—underscore the importance of comprehensive carbon assessments to determine actual climate benefits.

C. *Would CDR Be Socially or Politically Acceptable?*

In addition to concerns regarding CDR's technical feasibility and effectiveness, questions also surround its social and political acceptability. Because CDR directly addresses the rising GHG levels that lead to climate change, it is generally viewed as less risky than the other major category of geoengineering techniques, solar radiation management (SRM). SRM aims to combat climate change without lowering atmospheric GHG levels by reflecting a portion of the Sun's radiation.⁸¹ SRM would generally introduce novel global

72. See NAS CDR, *supra* note 7, at 52.

73. See CBD 84, *supra* note 6, at 58.

74. See WG1AR5, *supra* note 16, at 546.

75. See NAS CDR, *supra* note 7, at 25.

76. See *id.*

77. See WG3AR5, *supra* note 23, at 485; NAS CDR, *supra* note 7, at 25; see also C.D. Jones et al., *Simulating the Earth System Response to Negative Emissions*, 11 ENVTL. RESEARCH LETTERS 095012, 10 (2016) (suggesting that the effect of CDR on atmospheric CO₂ “is more closely controlled by the background scenario and level of climate change than by the amount or timing of NETs themselves”).

78. See Williamson, *supra* note 21, at 154.

79. See CBD 84, *supra* note 6, at 60.

80. See Williamson, *supra* note 21, at 155.

81. See NAS CDR, *supra* note 7, at 3.

risks, whereas most types of CDR would not.⁸² These differences apparently explain an observable—albeit tentative—public preference for CDR over SRM.⁸³ CDR deployment will not necessarily be free of controversy, however. Focus group discussions of CDR suggest that concerns about intragenerational and intergenerational equity could loom large.⁸⁴ And just as biofuels and wind energy have encountered resistance after concrete policies were established and specific projects proposed, CDR could encounter substantial opposition once the impacts of large-scale implementation become clear.⁸⁵ In light of the social implications of CDR deployment, evaluating CDR's social feasibility is as essential as determining its technical feasibility.⁸⁶

Consider the social feasibility of BECCS, for example. Public familiarity with BECCS, as well as research on public perception of BECCS, is relatively limited.⁸⁷ Nevertheless, proposals to cultivate bioenergy crops have encountered opposition in some countries because of worries about rising food prices.⁸⁸ In addition, studies of public views on CCS—a critical component of BECCS and DACS—reveal specific concerns that underground carbon storage could lead to leaks or earthquakes and general unease that CCS might facilitate continued fossil fuel consumption.⁸⁹ Such views are not deeply entrenched, however. If framed as part of a permanent solution to climate change, BECCS or DACS might receive more public support than CCS alone.⁹⁰

In seeking to understand BECCS' social ramifications, studies of efforts to expand production of first-generation biofuels could provide useful insights. First-generation biofuels are produced from sugar, starch, and oilseed crops, whereas second-generation biofuels are produced from woody crops or agricultural residue.⁹¹ Accordingly, first-generation biofuels are more likely to conflict with food production than the second-generation biofuels that BECCS

82. *See id.*

83. *See* Dirk Scheer & Ortwin Renn, *Public Perception of Geoengineering and its Consequences for Public Debate*, 125 *CLIMATIC CHANGE* 305, 309 (2014) (cautioning that public opinion on geoengineering remains relatively undeveloped because of unfamiliarity with the subject).

84. *See* Duncan McLaren et al., *Public Conceptions of Justice in Climate Engineering: Evidence from Secondary Analysis of Public Deliberation*, 41 *GLOB. ENVTL. CHANGE* 64, 69 (2016).

85. *See* Meadowcroft, *supra* note 8, at 146–47 (“Typically it is only as a technology is rolled out into society that one can get a firm grip on the timing and strength of side effects, the operation of countervailing society, and the mobilization of direct opposition.”).

86. *See* Buck, *supra* note 33, at 156.

87. *See* Kemper, *supra* note 43, at 418.

88. *See* Fuss et al., *supra* note 13, at 7; *see also* S. Schäfer et al., *The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth*, European Union's Seventh Framework Programme under Grant Agreement 306993, 117 (2015), <https://www.adelphi.de/en/system/files/mediathek/bilder/EuTRACE%20Final%20Report.pdf> (noting public opposition to CCS and BECCS in some European countries and need for enhanced public dialogue about BECCS).

89. *See* Buck, *supra* note 33, at 159.

90. *See* Kemper, *supra* note 43, at 419; Buck, *supra* note 33, at 159.

91. *See* Arnold W. Reitze, Jr., *Biofuel and Advanced Biofuel*, 33 *UCLA J. ENVTL. L. & POL'Y* 309, 312–13 (2015).

would use.⁹² Both types of biofuels involve competing land uses, however. First-generation biofuel crops have prompted worries about not only food insecurity and higher food prices, but also other socioeconomic concerns. Studies of first-generation biofuel crop production have found that (1) biofuel crop production displaced subsistence crops; (2) using land for biofuel crop production rather than subsistence farming “lock[ed] land and labor into relatively inflexible arrangements” and increased dependence on world markets; and (3) land slated for biofuel production was sometimes purchased for speculative gain rather than used to produce biofuels.⁹³

Studies of projects aimed at storing carbon in forests suggest that these projects have benefited foreign investors and elites, and developing countries have not always managed projects effectively.⁹⁴ In addition, a lack of clear property rights sometimes left indigenous peoples and local communities vulnerable to exploitation.⁹⁵ The cultivation of bioenergy crops for BECCS or other land-intensive CDR techniques such as biochar could face similar complications. Undertaking CDR techniques on the scale anticipated by climate modelers would almost surely lead to conflict with local communities.

Widespread deployment of other CDR techniques also could provoke resistance. Ocean fertilization experiments have generated controversy based on the technique’s potentially undesirable ecological impacts.⁹⁶ Installing thousands of air capture devices, even in less visible locations, could trigger a backlash akin to that associated with large-scale wind farms.⁹⁷ The massive amount of mining activity required by enhanced weathering also could be controversial.

Prospective opposition to CDR does not preclude using CDR. However, the potential for conflict does suggest the importance of early and ongoing engagement with communities likely to be affected. Furthermore, the difficulties encountered in expanding production of first-generation biofuel crops warn against overly optimistic projections regarding CDR deployment. It is simply unrealistic to assume the rapid deployment of CDR across wide swaths of land and in numerous countries of varying capacity and willingness. Research to analyze CDR’s social feasibility will be an essential component of evaluating CDR’s prospects for helping to achieve the 2C goal.

92. See Buck, *supra* note 33, at 160.

93. *Id.*

94. See *id.* at 163.

95. See Kartha & Dooley, *supra* note 13, at 8.

96. See Phillip Williamson et al., *Ocean Fertilization for Geoengineering: A Review of Effectiveness, Environmental Impacts and Emerging Governance*, 90 PROCESS SAFETY & ENVTL. PROT. 475, 483 (2012).

97. See Katharine Q. Seelye, *After 16 Years, Hopes for Cape Cod Wind Farm Float Away*, N.Y. TIMES (Dec. 19, 2017), <https://www.nytimes.com/2017/12/19/us/offshore-cape-wind-farm.html> (noting litigation and political opposition that led to abandonment of Cape Wind project).

II. HOW DOES CDR FIT WITHIN THE INTERNATIONAL CLIMATE REGIME?

As the preceding discussion indicates, CDR techniques are not mature and face formidable obstacles to full-scale deployment. Not surprisingly, the legal regime for CDR is relatively undeveloped as well, although the Paris Agreement quietly assumes a significant role for CDR. This Part considers specific provisions of the United Nations Framework Convention on Climate Change (Framework Convention) and the Paris Agreement that may govern CDR's legal status. Together, these agreements lay the foundation for widespread CDR implementation without explicitly committing to it.

From the outset, the international climate regime has recognized the potential human influence on various processes in which Earth's forests, land, and oceans remove GHGs from the atmosphere. Afforestation and reforestation, sometimes characterized as CDR techniques, are accepted means of reducing emissions under the Kyoto Protocol's Clean Development Mechanism.⁹⁸ While the status of other forms of CDR, including BECCS and DACS, is less certain under international law, they could be accommodated by the existing climate regime.

A. *The Framework Convention on Climate Change*

The Framework Convention focused international attention on climate change and established a process for the international community to take further steps to address the problem. However, the agreement created no binding obligations to decrease GHG emissions and made no direct mention of CDR. Several of its key provisions nonetheless could serve as a basis for incorporating CDR into an international climate change response and establishing a system of CDR oversight.

First, the Framework Convention's declared objective is "to achieve *stabilization of greenhouse gas concentrations* in the atmosphere at a level that would avoid dangerous anthropogenic interference with the climate system."⁹⁹ By definition, CDR techniques aim to remove GHGs from the atmosphere. In negotiating the Framework Convention, the international community assumed that directly reducing GHG emissions would be the primary means of stabilizing GHG concentrations, but the agreement does not rule out alternative approaches.

Second, the concepts of GHG sinks and reservoirs, which play a significant role in the Framework Convention, are defined in such a way as to potentially encompass CDR. The treaty defines "sink" as "any process or activity which removes a [GHG] . . . from the atmosphere" and "reservoir" as "a component . . . of the climate system where a [GHG] . . . is stored."¹⁰⁰ These definitions are not

98. See THE ROYAL SOCIETY, *supra* note 6, at 10; Kyoto Protocol to the United Nations Framework Convention on Climate Change, Dec. 11, 1997, 2303 U.N.T.S. 156, art. 3.3. [hereinafter Kyoto Protocol].

99. United Nations Framework Convention on Climate Change, May 9, 1992, S. Treaty Doc. No. 102-38, 1771 U.N.T.S. 164, art. 2 [hereinafter Framework Convention] (emphasis added).

100. *Id.* at art. 1.8, 1.9.

limited to natural processes and thus could include components of CDR technologies.¹⁰¹ The primary commitments of the Framework Convention, found in Article 4, include several references to sinks and reservoirs. All Framework Convention parties have pledged to formulate and implement “programmes containing measures to mitigate climate change by addressing anthropogenic emissions by sources and removals by sinks” and to “[p]romote sustainable management” and “conservation and enhancement” of sinks and reservoirs, “including biomass, forests and oceans.”¹⁰² Developed country parties have further agreed to take measures to “protect[] and enhance[] . . . sinks and reservoirs.”¹⁰³ These provisions appear to be consistent with proposed CDR techniques, which in removing GHGs from the atmosphere and storing them elsewhere, arguably would function as sinks or reservoirs.

B. The Paris Agreement

Like the Framework Convention, the Paris Agreement does not mention CDR explicitly. An early draft of the agreement did suggest a possible long-term goal of achieving “negative emissions” (among a menu of options),¹⁰⁴ but even such brief references to CDR did not survive the negotiation process. The final version of the Paris Agreement does not preclude CDR, however, and various provisions appear implicitly to contemplate its use. Indeed, economic modeling of possible pathways for achieving the agreement’s ultimate objective suggest that substantial and increasing amounts of CDR will be necessary.

Several provisions of the Paris Agreement are potentially relevant to CDR. First, individual states must prepare nationally determined contributions (NDCs) to global action on climate change and “pursue domestic mitigation measures, with the aim of achieving . . . such contributions.”¹⁰⁵ The NDCs lie at the heart of the agreement, and their combined effect will determine whether the 2C goal is met. The references to mitigation in the NDC provisions, as well as other provisions calling for reducing or limiting emissions,¹⁰⁶ reflect an overall emphasis on diminished GHG releases. At the same time, however, other parts

101. See A. NEIL CRAIK & WILLIAM C.G. BURNS, CTR. FOR INT’L GOVERNANCE INNOVATION, CLIMATE ENGINEERING UNDER THE PARIS AGREEMENT: A LEGAL AND POLICY PRIMER 6 (2016). The 2011 decision to recognize carbon capture and sequestration as a permissible type of Clean Development Mechanism project is consistent with this interpretation of the Framework Convention. *Id.* at 7.

102. Framework Convention, *supra* note 99, at art. 4.1(b), (d).

103. *Id.* at art. 4.2(a).

104. Ad Hoc Working Group on the Durban Platform for Enhanced Action, Work of the Contact Group on Item 3 Negotiating Text 6, 9 (Feb. 12, 2015), https://unfccc.int/files/bodies/awg/application/pdf/negotiating_text_12022015@2200.pdf.

105. U.N. Framework Convention on Climate Change (UNFCCC), Adoption of the Paris Agreement, Dec CP.21, 21st Sess., at art. 4.2, UN Doc FCCC/CP/2015/L.9 (Dec. 12, 2015) [hereinafter Paris Agreement]. One review found only 10 of 162 NDCs mentioned CCS. INTERNATIONAL ENERGY AGENCY, 20 YEARS OF CARBON CAPTURE AND STORAGE: ACCELERATING FUTURE DEPLOYMENT 68 (2016) [hereinafter IEA 2016].

106. Paris Agreement, *supra* note 105, at art. 4.4.

of the agreement do acknowledge the potential significance of GHG removal. Parties are “to achieve a balance between anthropogenic emissions by sources and removals by sinks . . . in the second half of this century” and to consider both anthropogenic emissions and removals in accounting for their NDCs.¹⁰⁷ These mentions of anthropogenic removals arguably refer first and foremost to forest-related strategies that have already been integrated into the international climate regime.¹⁰⁸ Indeed, one article of the Paris Agreement calls on parties to promote the conservation and enhancement of sinks and reservoirs and specifically singles out forests.¹⁰⁹

Other Paris provisions also could be relevant to CDR.¹¹⁰ Of particular interest, Article 6 would establish a sustainable development mechanism roughly analogous to the Kyoto Protocol’s Clean Development Mechanism.¹¹¹ The sustainable development mechanism could serve as a vehicle for generating and trading carbon removal credits in a manner akin to the trading between countries of emissions reduction credits generated through the Clean Development Mechanism.¹¹² Establishing a market in carbon removal credits would attract private investment in CDR and stimulate CDR development efforts. While the sustainable development mechanism will likely focus on reducing GHG emissions rather than removing GHGs from the atmosphere, it could offer a mechanism for leveraging the private resources needed to accomplish CDR on a broad scale.¹¹³

Although the Paris Agreement is consistent with CDR, the agreement text itself offers little sense of CDR’s significance. In contrast, the modeling relied on by negotiators in setting the agreement’s objective, rather than the text, reveals CDR’s critical role. Paris’s objective is to “[h]old[] the increase in the global average temperature to well below 2°C above pre-industrial levels and pursu[e] efforts to limit the temperature increase to 1.5°C above pre-industrial levels.”¹¹⁴ To achieve the less ambitious 2C goal, cumulative future emissions will have to be limited to between 600 and 1200 Gt CO₂.¹¹⁵ Under the optimistic

107. *Id.* at art. 4.1, 4.13, 4.14.

108. *See infra* Part III.A.

109. Paris Agreement, *supra* note 105, at art. 5.1 (“Parties should take action to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases as referred to in Article 4, paragraph 1(d), of the Convention, including forests.”).

110. *See* CRAIK & BURNS, *supra* note 101, at 10–11 for further discussion.

111. Paris Agreement, *supra* note 105, at art. 6. The Kyoto Protocol established binding obligations on developed countries to reduce their GHG emissions. A party could satisfy these obligations by directly reducing emissions itself or by arranging for emissions reductions in other countries. *See* Kyoto Protocol, *supra* note 98, at art. 3, 12, 17.

112. Paris Agreement, *supra* note 105, at art. 6.4; *see* Karen Holm Olsen et al., *Learning from the CDM SD Tool Experience for Article 6.4 of the Paris Agreement*, 18 CLIMATE POLICY 383, 383 (2018).

113. *See* CRAIK & BURNS, *supra* note 101, at 8.

114. Paris Agreement, *supra* note 105, at art. 2.1(a).

115. *See* Anderson & Peters, *supra* note 2, at 182.

assumption that annual emissions remain steady at present levels, this so-called carbon budget could be used up in less than two decades.¹¹⁶

In calculating how the 2C goal might be achieved, researchers apply integrated assessment models (IAM) to estimate the economically optimal choice between mitigation, CDR, or a combination of the two.¹¹⁷ Modeling runs generally project significant CDR deployment commencing well before midcentury and a further ramp-up in CDR deployment through 2100.¹¹⁸ Such results, which assume both declining CDR costs and an increasing price on carbon,¹¹⁹ are not surprising in light of the limited remaining carbon budget. These projections, it should be kept in mind, represent estimates of the economically optimal path for achieving the 2C goal, *not* predictions about what is likely to happen.

One commentary contends that the Paris Agreement “marks a major upgrade in the role envisioned for CDR technologies in climate policy.”¹²⁰ The Paris Agreement’s “highly ambitious temperature targets, . . . explicit mentioning of anthropogenic removals, and . . . commitment to achieve a ‘balance’ between emissions and removals” all could be interpreted as positive signals for CDR.¹²¹ In contrast, other observers have characterized the Paris Agreement as a fantasy in which “the world has just gambled its future on the appearance in a puff of smoke of a carbon-sucking fairy godmother.”¹²² This latter view also recognizes the pivotal role of CDR under the Paris Agreement, but deems it to be unrealistic.

Indeed, the feasibility of CDR on the scale assumed by IAM modeling runs is highly questionable.¹²³ The modeling makes no effort to seriously examine assumptions regarding CDR readiness and availability.¹²⁴ None of the NDCs

116. *See id.* (noting annual emissions of approximately forty Gt CO₂). Current projections are for emissions to continue to rise until 2030 even if the current Paris pledges are implemented. *See id.*

117. *See* Fuss et al., *Betting*, *supra* note 10, at 851.

118. *See* Anderson & Peters, *supra* note 2, at 182; *see also* Williamson, *supra* note 21, at 155 (estimating that “significant CO₂ removal will need to begin around 2020, with up to twenty gigatonnes of CO₂ extracted each year by 2100” in order to avoid 2°C increase); Fuss et al., *Betting*, *supra* note 10, at 850 (stating that scenarios based on integrated assessment models assume removal of 1000 Gt CO₂ through 2100 in order to avoid 2°C increase).

119. *See* POSTNOTE, *supra* note 9, at 3. Whether such assumptions are warranted is questionable, however. *See id.*

120. Joshua B. Horton et al., *Implications of the Paris Agreement for Carbon Dioxide Removal and Solar Geoengineering*, HARV. PROJECT ON CLIMATE AGREEMENTS 3 (July 2016).

121. *Id.*

122. Kevin Anderson, *Talks in the City of Light Generate More Heat*, 528 NATURE 437, 437 (2015); *see also* Tim Kruger et al., *Abandon Hype in Climate Models*, GUARDIAN (Apr. 26, 2016), <https://www.theguardian.com/science/political-science/2016/apr/26/abandon-hype-in-climate-models> (characterizing agreement as “magical thinking”).

123. *See* EASAC, *supra* note 2, at 1 (concluding that CDR technologies “offer only limited realistic potential to remove carbon from the atmosphere and not at the scale envisaged in some climate scenarios”).

124. *See* Vaughan & Gough, WPD 1b, *supra* note 19, at 22 (reporting comment of expert participating in workshop on BECCS that CDR serves as “an artificial ‘get out of jail’ card”); EASAC, *supra* note 2, at 13 (characterizing such modeling as “rather optimistic” in that it fails to account fully for

submitted under the Paris Agreement mention CDR or any CDR technique aside from afforestation and other forest-related activities.¹²⁵ And while the agreement contemplates that countries will periodically revise their NDCs, the complete absence of CDR in the NDCs suggests that CDR is nowhere close to being economically or politically feasible.

None of this is meant to suggest that the Paris Agreement establishes a legal obligation to undertake CDR. However, serious contemplation of Paris's 2C goal underscores the need for concrete examination of how CDR will contribute to achieving that goal.

III. INSTRUCTIVE ANALOGIES FOR CDR

As explained above, the Framework Convention and Paris Agreement have quietly laid the groundwork for concerted CDR efforts. However, CDR implementation will not occur on its own. Incentives and rules will be needed to attract and structure investments of time and resources.

To get a sense of the challenges involved in CDR implementation, we can consider how the international climate regime has addressed forestry-related reductions in GHG emissions. Policy struggles with respect to other technologies also can offer valuable insights. U.S. renewable fuels policy and global efforts to promote CCS offer particularly useful comparisons. Indeed, the leading CDR proposal, BECCS, essentially combines these two approaches: large-scale cultivation and processing of bioenergy crops to provide energy, and capture and storage of large quantities of CO₂. Like renewable fuels and CCS, CDR technologies in general are a policy response to the negative externality of carbon emissions and could face similar economic disincentives and political resistance to their development.

A. *Forests under the Framework Convention Regime*

The Framework Convention's approach to forestry and related land-use changes could prove relevant to CDR governance in several ways. First, the mechanisms developed in this context apply to afforestation and other land management activities that are sometimes classified as CDR. Second, these mechanisms might serve as models for incentivizing other types of CDR. Third and perhaps most importantly, experience in developing these mechanisms reveals some of the barriers to scaling up carbon reduction efforts based on land use. These barriers include the development of accounting, recordkeeping, and

factors that may reduce CDR capacity, including competition for resources among different types of CDR techniques).

125. See Fuss et al., *Research Priorities*, *supra* note 13, at 7; see also Glen P. Peters & Oliver Geden, *Catalysing a Political Shift from Low to Negative Carbon*, 7 *NATURE CLIMATE CHANGE* 619, 619 (2017) (noting that no countries have mentioned BECCS in their NDCs and that only about a dozen even mention carbon capture and storage). A number of NDCs do include reforestation, forest management, or coastal habitat restoration—methods of boosting carbon sinks that often are not classified as CDR. *Id.*

monitoring requirements to ensure actual carbon removal, the securing of financing, and the implementation of policies at national and subnational levels.

The international community has long recognized that forestry and other land management activities may generate or sequester GHG emissions in significant quantities.¹²⁶ However, in contrast to other sectors where reducing GHG emissions was relatively straightforward, forestry-related emissions was a more complex task that required significant time and resources to address.¹²⁷ As discussed below, it took two decades to incorporate forestry-related emissions into the international climate regime.

The relatively sparse data on forests and forestry-related emissions, combined with a lack of standardized methodologies for measuring and reporting such data, gave rise to concerns regarding the integrity and verifiability of emissions reductions.¹²⁸ Ideally, accurate carbon accounting would ensure that emissions reductions are permanent and additional—determinations that can be especially difficult to make in the forestry context.¹²⁹ Carbon accounting efforts also should consider leakage—the potential displacement of emissions to other locations.¹³⁰ Specifically, incentivizing afforestation projects for carbon removal in one place could encourage deforestation (and increased carbon emissions) in other places.¹³¹

A divide between forest-rich and forest-poor countries also slowed negotiation progress on forestry-related emissions. Countries with substantial forests viewed forestry activities as a cost-effective way to offset GHG emissions from other sectors and thus supported the inclusion of forests within the climate regime.¹³² Countries with more limited potential to sequester carbon in forests opposed using forests as an offset.¹³³ Developing countries were especially reluctant to allow industrialized countries to rely on forest carbon removal as a means of avoiding more onerous mitigation responsibilities.¹³⁴

126. See, e.g., Framework Convention, *supra* note 99, at art. 4.1(c), (d).

127. See generally Giacomo Grassi et al., *The Key Role of Forests in Meeting Climate Targets Requires Science for Credible Mitigation*, 7 NATURE CLIMATE CHANGE 220, 220 (2017); Antonio G.M. La Viña et al., *History and Future of REDD+ in the UNFCCC: Issues and Challenges*, in RESEARCH HANDBOOK ON REDD+ AND INTERNATIONAL LAW 11 (Christina Voigt ed., 2016); Alexander Gillespie, *Sinks and the Climate Change Regime: The State of Play*, 13 DUKE ENVTL. L. & POL'Y F. 279, 284–86 (2003).

128. David A. Wirth, *The Sixth Session (Part Two) and Seventh Session of the Conference of the Parties to the Framework Convention on Climate Change*, 96 AM. J. INT'L L. 648, 653–54 (2002).

129. FOOD & AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, FORESTRY FOR A LOW-CARBON FUTURE 10 (2016) [hereinafter FAO REPORT] (explaining that carbon stored in trees is eventually released as a result of natural mortality, pest outbreaks, fires, or decay).

130. See *id.*

131. See *id.* at 82.

132. Rômulo Silveira da Rocha Sampaio, *Seeing the Forest for the Treaties: The Evolving Debates on Forest and Forestry Activities Under the Clean Development Mechanism Ten Years After the Kyoto Protocol*, 31 FORDHAM INT'L L.J. 634, 644 (2008).

133. *Id.*

134. FAO REPORT, *supra* note 129, at 10.

The international community ultimately agreed on three mechanisms to account for forestry-related reductions in GHG emissions under the Framework Convention regime: (1) in developed countries, determinations of compliance with the Kyoto Protocol's nationwide emissions caps include forestry-related emissions;¹³⁵ (2) in developing countries, afforestation and reforestation projects can generate carbon credits through the Clean Development Mechanism;¹³⁶ and (3) reduced emissions from deforestation and forest degradation in developing countries can generate financial compensation (REDD+).¹³⁷ The Paris Agreement softens the distinctions between these categories, but generally encourages the continuation of forestry-related mitigation efforts.¹³⁸

1. *Forestry-Related Emissions in Developed Countries*

The Kyoto Protocol required developed countries to reduce their overall GHG emissions below certain assigned amounts.¹³⁹ Calculations of a country's total emissions included net emissions resulting from "afforestation, reforestation and deforestation."¹⁴⁰ These terms were not defined by the protocol, however. In addition, the protocol left open the question of how, or whether, to account for forest management and other land-use related activities.¹⁴¹ These ambiguities raised the possibility that some countries might rely primarily on forest restocking or forest management to meet their Kyoto commitments, rather than on activities that were more certain to reduce GHG emissions, such as decreased consumption of fossil fuels.¹⁴² To address these concerns, the parties to the Kyoto Protocol adopted rules clarifying that countries would not receive credit for restocking recently harvested areas.¹⁴³ Rules also imposed a cap on parties' ability to meet their commitments by relying on GHG

135. See Kyoto Protocol, *supra* note 98, at art. 3.3, 3.4.

136. See Sebastian Thomas et al., *Why Are There So Few Afforestation and Reforestation Clean Development Mechanism Projects?*, 27 LAND USE POL'Y 880, 880–81 (2010); FAO REPORT, *supra* note 129, at 12.

137. See La Viña et al., *supra* note 127, at 12–13.

138. See Paris Agreement, *supra* note 105, at art. 5.2 (explicitly recognizing the role of REDD+ in achieving the Nationally Determined Contributions (NDCs) of each country); FAO REPORT, *supra* note 129, at 18–19 (analyzing importance of forestry in NDCs); Grassi et al., *supra* note 127, at 220 (characterizing Paris Agreement as "a potential game changer" for mitigation relating to land use).

139. Kyoto Protocol, *supra* note 98, at art. 3.1.

140. *Id.* at art. 3.3; See DAVID HUNTER ET AL., INTERNATIONAL ENVTL. LAW & POLICY 707 (5th ed. 2015).

141. Kyoto Protocol, *supra* note 98, at art. 3.4. This category of activities is sometimes referred to under the term "land use, land use change and forestry (LULUCF)."

142. See HUNTER ET AL., *supra* note 140, at 707–08; FAO REPORT, *supra* note 129, at 10 ("forest mitigation options were long perceived as a potential threat to the environmental integrity of the overall mitigation framework").

143. See Geoffrey J. Aguirre, *Why Cutting Down Trees Is Part of the Problem, But Planting Trees Isn't Always Part of the Solution: How Conceptualizing Forests as Sinks Can Work Against Kyoto*, 11 OR. REV. INT'L L. 205, 209–11 (2009).

emissions reductions from forest management.¹⁴⁴ These technically complex rules were adopted only after lengthy negotiations.¹⁴⁵

Comprehensive accounting of GHG emissions should include emissions from forestry-related activities. However, critics have charged that a narrow focus on forests' carbon benefits can give short shrift to impacts on biodiversity.¹⁴⁶ Similar concerns are likely to arise in connection with efforts to integrate CDR into the international climate regime. Incentives for CDR will have to be balanced against measures to protect food security, water availability, biodiversity, and other matters of concern.

2. Forestry Projects under the CDM

Under the Kyoto Protocol's Clean Development Mechanism (CDM), developed countries can obtain emissions reduction credits for financing emissions reduction activities in developing countries.¹⁴⁷ CDM projects have involved a wide range of activities and have been a popular source of GHG credits.¹⁴⁸ However, the CDM has been widely criticized for creating an incentive to undertake projects that generate GHG credits while yielding little actual environmental benefit.¹⁴⁹ Credits are awarded by measuring GHG emissions avoided as compared to a hypothetical baseline.¹⁵⁰ These baselines are subject to manipulation and may incorporate unverifiable projections about future emissions levels.¹⁵¹ Such concerns complicated negotiations surrounding forestry-related activities and led to the establishment of rules that exclude from CDM eligibility forestry-related projects other than those involving afforestation and reforestation.¹⁵²

Less than 1 percent of the thousands of CDM projects have involved forestry.¹⁵³ In comparison to other potential CDM activities, afforestation or reforestation projects are relatively unattractive because they involve high

144. See UNFCCC, Review of the Implementation of Commitments and of other Provisions of the Convention, FCCC/CP/2001/L.7, at 10–11 (July 24, 2001) [hereinafter Bonn Agreement]; FAO REPORT, *supra* note 129, at 10–11; HUNTER ET AL., *supra* note 140, at 708.

145. See Wirth, *supra* note 128, at 660.

146. See Aguirre, *supra* note 143, at 221.

147. Kyoto Protocol, *supra* note 98, at art. 12.

148. Michael Wara, *Measuring the Clean Development Mechanism's Performance and Potential*, 55 UCLA L. REV. 1759, 1775, 1778–80 (2008) (discussing projects used to generate emission credits under CDM).

149. See, e.g., *id.* at 1763–64; Harro van Asselt & Joyeeta Gupta, *Stretching Too Far? Developing Countries and the Role of Flexibility Mechanisms Beyond Kyoto*, 28 STAN. ENVTL. L.J. 311, 344–45 (2009); David Campbell et al., *After Cancun: The Impossibility of Carbon Trading*, 29 U. QUEENSLAND L.J. 163, 179–81 (2010) (criticizing CDM projects in China).

150. See Wara, *supra* note 148, at 1771.

151. See *id.* at 1763–64; Asselt & Gupta, *supra* note 149, at 344–45.

152. See Sampaio, *supra* note 132, at 656–59.

153. See CDM Projects by Type, UNEP DTU PARTNERSHIP (Feb. 2018), <http://www.cdmpipeline.org/cdm-projects-type.htm> (reporting that, as of February 2018, 71 out of 8362 CDM projects involved afforestation or reforestation). The only forestry-related activities eligible for CDM certification are afforestation and reforestation. Bonn Agreement, *supra* note 144, at 11.

transaction costs, produce delayed revenue streams, and require substantial financing until revenue streams begin.¹⁵⁴ Accounting and recordkeeping requirements are considerable, as project sponsors must establish baselines, calculate GHGs sequestered, account for leakage, and demonstrate that emissions reductions are additional and permanent.¹⁵⁵ Such projects face other obstacles as well, including unclear property rights, potential project failure, exclusion of forestry credits by some emissions trading schemes, and difficulty in coordinating landowners, investors, and government authorities.¹⁵⁶ CDM projects that do not involve carbon sinks—such as installing renewable energy or switching to less carbon-intensive fuels—face fewer and less complex registration requirements.¹⁵⁷

The CDM's struggles to bring about afforestation and reforestation projects offer a cautionary tale for CDR efforts. CDR projects likely would face comparable obstacles: project sponsors would have to establish baselines, determine the quantity of GHGs sequestered, demonstrate permanence, and account for leakage. Land-intensive CDR projects would have to grapple with uncertain property rights, land-use conflicts, and logistical complexities comparable to afforestation projects. In addition, the high costs of CDR projects could make them unattractive compared to other carbon reducing options.

3. REDD+

Efforts to incorporate developing country forests into the international climate regime have centered on the REDD+ mechanism (referring to “reducing emissions from deforestation and forest degradation”) rather than the CDM. Under REDD+, which operates at a national level rather than on a project-by-project basis, developing countries receive compensation for reducing forest-related carbon emissions.¹⁵⁸ To earn these results-based payments, developing countries must establish and implement a national REDD+ strategy.¹⁵⁹ The components of such a strategy include an action plan setting out goals, targets,

154. See Thomas et al., *supra* note 136, at 881.

155. See *id.* at 882; FAO REPORT, *supra* note 129, at 10.

156. See Thomas et al., *supra* note 136, at 882; FAO REPORT, *supra* note 129, at 14; Yazhen Gong et al., *Participation in the World's First Clean Development Mechanism Forest Project: The Role of Property Rights, Social Capital and Contractual Rules*, 69 ECOLOGICAL ECON. 1292, 1300 (2010).

157. See Maria Nijnik & Pradipta Halder, *Afforestation and Reforestation Projects in South and South-East Asia Under the Clean Development Mechanism: Trends and Development Opportunities*, 31 LAND USE POL'Y 504, 505 (2013).

158. See FAO REPORT, *supra* note 129, at 16. For an overview of REDD+, see Julian Michel et al., *Reducing Emissions from Deforestation and Forest Degradation (REDD)*, in TROPICAL FORESTRY HANDBOOK (Laslo Pancel & Michael Köhl eds., 2015). While REDD+ focuses on national-level efforts, the mechanism calls for the development of demonstration projects linked to national strategies. Esther Turnhout et al., *Envisioning REDD+ in a Post-Paris Era: Between Evolving Expectations and Current Practice*, 8 WIREs CLIMATE CHANGE, Jan.–Feb. 2017, at 1, 3.

159. See FAO REPORT, *supra* note 129, at 16, 40. About 90 percent of REDD+ funding comes from public sources, and the remainder from private sources, as disbursed through voluntary carbon markets. Turnhout et al., *supra* note 158, at 3.

and principles; measuring, reporting, and verification procedures; baselines against which a country's performance will be measured; a registry to track REDD+ activities; and a system of safeguards to identify and address impacts on communities and ecosystems.¹⁶⁰

For a number of reasons, however, REDD+ has only begun to yield concrete reductions in carbon emissions. As an initial matter, putting in place rules, standards, and procedures for implementing REDD+ took over a decade.¹⁶¹ Originally conceptualized as a climate change mitigation strategy, the program's objectives have expanded over time to incorporate tropical forest conservation and sustainable development as well.¹⁶² In addition, the scope of REDD+ has broadened from an early focus on deforestation to include forest degradation, conservation, and management.¹⁶³ These changes to REDD+ responded to serious concerns and were not necessarily inappropriate. However, the lengthy process of negotiating, developing, and integrating these changes to REDD+ offers a cautionary note for CDR. CDR policy should be concerned with not only the efficacy of carbon removal, but also the development of metrics that account for environmental and social impacts.

Establishing adequate financing for REDD+ has proven to be a further challenge.¹⁶⁴ In the absence of mandatory carbon pricing, REDD+ relies heavily on voluntary contributions by multilateral institutions and individual nations.¹⁶⁵ Though supplemented by private funding from voluntary carbon markets, such contributions have been insufficient to fund REDD+ programs.¹⁶⁶ Even where funding has been committed, often only a fraction of it has been disbursed, suggesting "implementation-related problems or inefficiencies in financial delivery mechanisms."¹⁶⁷ Furthermore, REDD+ funding thus far has been directed primarily to "readiness activities"—"developing policy, building capacity and strengthening national institutions in-country, as well as developing monitoring and MRV systems"—as opposed to carrying out on the ground activities to reduce carbon emissions.¹⁶⁸ Implementing CDR will require similar resource-intensive preparatory work as well as funding to support actual implementation. As has been the case with REDD+, funding for CDR will likely

160. See Michel et al., *supra* note 158, at 6–13.

161. See La Viña et al., *supra* note 127, at 12–19.

162. See Michel et al., *supra* note 158, at 2.

163. See Annecoos Wiersma, *Climate Change, Forests, and International Law: REDD's Descent into Irrelevance*, 47 VAND. J. TRANSNAT'L L. 1, 24–35 (2014).

164. See Turnhout et al., *supra* note 158, at 3; FAO REPORT, *supra* note 129, at 41.

165. See Turnhout et al., *supra* note 158, at 3.

166. See Robert Fletcher et al., *Questioning REDD+ and the Future of Market-Based Conservation*, 30 CONSERVATION BIOLOGY 673, 674 (2016).

167. FAO REPORT, *supra* note 129, at 41.

168. DONNA LEE & TILL PISTORIUS, THE IMPACTS OF INTERNATIONAL REDD+ FINANCE 11 (2015). "MRV" refers to measurement, reporting, and verification provisions for climate change mitigation. See Neelam Singh et al., *MRV 101: Understanding Measurement, Reporting, and Verification of Climate Change Mitigation* (World Resources Institute, Working Paper, Aug. 2016), https://wri.org/sites/default/files/MRV_101_0.pdf.

fall short unless a mandatory carbon price or similar mechanisms are put in place to incentivize CDR projects.

Sovereignty concerns have also slowed implementation of REDD+ on the ground. In response to concerns that REDD+ would cause indirect land-use change and social and environmental impacts,¹⁶⁹ countries participating in REDD+ must adhere to social and environmental safeguards while implementing REDD+ activities.¹⁷⁰ However, worried that they might lose sovereign control over land use, developing countries blocked efforts to establish a centralized process to review compliance with these safeguards.¹⁷¹ Sovereignty concerns also have prompted local opposition to some REDD+ pilot projects.¹⁷²

Conflicts rooted in sovereignty highlight the fact that “[m]uch of the actual activity of implementing [REDD+] and its safeguards will occur at the national and local levels of governance” with limited international oversight.¹⁷³ Although CDR mechanisms need not mirror the REDD+ approach, nation-states are likely to play a central role in CDR implementation, too. First, institutions of international environmental law are relatively weak, relying heavily on implementation at national or subnational levels.¹⁷⁴ Second, the Paris Agreement’s use of NDCs as a central organizing principle reflects a trend toward greater national autonomy within the international climate regime. Accordingly, sovereignty concerns could prove a roadblock to implementation, particularly for land-intensive techniques such as BECCS. Even seemingly technical matters, such as the negotiation of carbon accounting rules and monitoring requirements, could become the subject of politically contentious disputes.¹⁷⁵

Notwithstanding the difficulties encountered in its development, REDD+ appears set to continue under the Paris Agreement.¹⁷⁶ The agreement encourages parties “to conserve and enhance . . . sinks and reservoirs of greenhouse gases . . . including forests,” and to support policies and incentives for reducing emissions from forest-related activities.¹⁷⁷ Although the agreement does not

169. See FAO REPORT, *supra* note 129, at 47; Turnhout et al., *supra* note 158, at 2.

170. See Blaise Bodin et al., *Putting REDD+ Environmental Safeguards into Practice: Recommendations for Effective and Country-Specific Implementation*, 2 CARBON & CLIMATE L. REV. 168, 168–70 (2015).

171. See *id.* at 171.

172. Fletcher et al., *supra* note 166, at 674 (noting suspicion of “outsiders arriving with promises of future benefits”).

173. Wiersma, *supra* note 163, at 57–58, 64.

174. DANIEL BODANSKY, *THE ART AND CRAFT OF INTERNATIONAL ENVIRONMENTAL LAW* 109–17 (2010) (discussing international environmental law operating “largely as a system of law between states rather than regulating conduct more broadly” and noting that international environmental law “has no international institution with general governance functions”).

175. Turnhout et al., *supra* note 158, at 4 (discussing carbon accounting for REDD+ and noting its framing “as technical matters to be negotiated and institutionalized within expert settings”).

176. Josefina Brana-Varela & Donna Lee, *Early Reflections on the Implications of the Paris Agreement for REDD+*, MERIDIAN INSTITUTE, at 9–10 (2016), <http://merid.org/ImplicationsofParisAgreement.aspx>.

177. Paris Agreement, *supra* note 105, at art. 5.2.

specify how REDD+ will be integrated into NDCs, one analysis of submitted NDCs estimates that forests could provide approximately a quarter of planned total emissions reductions through 2030.¹⁷⁸ Actually achieving these reductions from the forestry sector, however, will require improvements in the transparency, accuracy, consistency, completeness, and comparability of GHG inventories.¹⁷⁹ Developing robust and credible data poses both technical and practical challenges in the face of economic and political pressures to qualify for REDD+ payments.¹⁸⁰

Integrating CDR into the climate change regime and implementing CDR will face challenges similar to those encountered by REDD+. Unless the international community adequately addresses issues of financing, sovereignty, and accounting, CDR likely will not serve as a meaningful response to climate change.

B. The Renewable Fuels Standard

The renewable fuels standard (RFS) offers a further cautionary tale with respect to incentivizing land- and capital-intensive technologies intended to address climate change.

Established in 2005 and revised by the Energy Independence and Security Act of 2007, the RFS has been the federal government's primary instrument for promoting renewable fuels. The RFS' multiple objectives include promoting energy independence, reducing GHG emissions, stabilizing transportation fuel prices, and boosting rural economies.¹⁸¹ The RFS requires fuel refiners and importers to incorporate increasing volumes of various categories of biofuels into gasoline.¹⁸² These categories include: renewable fuels, which must have lifecycle GHG emissions at least 20 percent lower than a baseline; advanced biofuels, which must have at least 50 percent lower lifecycle GHG emissions; and cellulosic biofuels, which must have at least 60 percent lower lifecycle GHG emissions.¹⁸³ Thus, the RFS guaranteed a market not only for first-generation biofuels that had been available since the 1970s—specifically, corn ethanol—but also for second-generation biofuels, which at the time of the RFS enactment were still under development.¹⁸⁴ Regulated parties comply with the RFS by

178. See Grassi et al., *supra* note 127, at 225.

179. See *id.*

180. See Turnhout et al., *supra* note 158, at 4.

181. See KELSI BRACMORT, CONG. RESEARCH SERV., THE RENEWABLE FUEL STANDARD (RFS): CELLULOSIC BIOFUELS at 1 (2015) [hereinafter CRS 2015]; Jay Kesan et al., *An Empirical Study of the Impact of the Renewable Fuel Standard (RFS) on the Production of Fuel Ethanol in the U.S.*, 2017 UTAH L. REV. 159, 168 (2017).

182. 42 U.S.C. § 7545(o)(2) (2012); see Reitze, *supra* note 91, at 313–14.

183. 42 U.S.C. § 7545(o)(1)(B), (E), (J) (2012); Reitze, *supra* note 91, at 314.

184. See Kesan et al., *supra* note 181, at 166, 170.

submitting credits—called Renewable Information Numbers—which are generated when a biofuel is produced or imported.¹⁸⁵

1. Corn Ethanol

Industry lobbying has secured strong and consistent federal support for corn ethanol, notwithstanding doubts about the wisdom of such support.¹⁸⁶ Indeed, the RFS for corn ethanol has been widely criticized for harming society and the environment.¹⁸⁷ Using corn as fuel may reduce food availability, raise food prices, increase fertilizer and water use, and prompt the conversion of habitat to cropland.¹⁸⁸ Substituting corn ethanol for gasoline has reduced GHG emissions only modestly at best and may even increase total emissions after the GHGs released in habitat conversion are accounted for.¹⁸⁹ Moreover, the 20 percent emissions reduction mandated by the RFS does not apply to corn ethanol produced at facilities grandfathered in under the RFS.¹⁹⁰ Most of the corn ethanol used to meet the RFS mandate is produced by these older facilities and thus has generated little climate benefit.¹⁹¹

The corn ethanol RFS is of somewhat limited relevance to CDR policy because corn ethanol was a far more mature technology than CDR is today. Corn ethanol was being produced commercially through proven technologies well before adoption of the RFS.¹⁹² The RFS was unnecessary to stimulate development or use of corn ethanol, yet was adopted thanks to the backing of powerful agricultural interests.¹⁹³

In contrast to corn ethanol, even the most advanced CDR technologies today are far from commercialization, and affirmative policy measures will be needed to incentivize their development and use. Despite these differences, the corn ethanol RFS offers a warning to CDR policymakers that powerful economic and political interests can warp well-intentioned policies. At present, CDR lacks a powerful lobby behind it. However, one can imagine a scenario in which timber interests advocate BECCS or mining interests argue for enhanced weathering. Policymakers should be leery of favoring narrow interests at the potential

185. 42 U.S.C. § 7545(o)(5) (2012); Melissa Powers, *Lessons from US Biofuels Policy: The Renewable Fuels Standard's Rocky Ride*, THE LAW AND POLICY OF BIOFUELS 141, 146 (Yves Le Bouthillier et al. eds., 2016).

186. See Albert C. Lin, *Lessons from the Past for Assessing Energy Technologies for the Future*, 61 UCLA L. REV. 1814, 1829–30 (2014).

187. See, e.g., Powers, *supra* note 185, at 151; Reitze, *supra* note 91, at 321–35.

188. See T. Searchinger et al., *Do Biofuel Policies Seek to Cut Emissions by Cutting Food?*, 347 SCIENCE 1420, 1420 (2015).

189. See Mark Peplow, *Cellulosic Ethanol Fights for Life*, 507 NATURE 152, 152 (2014); Dan Charles, *Corn-Based Ethanol Flunks Key Test*, 324 SCIENCE 587, 587 (2009).

190. See 40 C.F.R. § 80.1403(c), (d); Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program, 75 Fed. Reg. 14,670, 14,688–89 (Mar. 26, 2010); Powers, *supra* note 185, at 151.

191. See Powers, *supra* note 185, at 151.

192. See Kesan et al., *supra* note 181, at 200; ROBERT ACKRILL & ADRIAN KAY, THE GROWTH OF BIOFUELS IN THE 21ST CENTURY: POLICY DRIVERS AND MARKET CHALLENGES 9 (2014).

193. See Lin, *supra* note 186, at 1828–30; Powers, *supra* note 185, at 161–62.

expense of climate benefits and of rashly choosing a specific CDR technology from among various unproven options.

2. *Second-Generation Biofuels*

Of greater relevance to CDR policy, the RFS for second-generation biofuels offers a case study in encouraging the development of a nascent technology. The RFS required cellulosic biofuel use beginning in 2010, mandated increasing use of such fuels in subsequent years, and envisioned that cellulosic biofuel would constitute 44 percent of all renewable fuel use by 2022.¹⁹⁴ Advanced biofuels, which include biofuels produced from noncorn feedstocks, are subject to similar requirements.¹⁹⁵

Actual use of cellulosic biofuel has fallen far short of anticipated amounts.¹⁹⁶ Production did not begin until 2012, and current volumes are less than 5 percent of statutory targets.¹⁹⁷ Various factors have contributed to the RFS' failure in this area. Uncertainty, both technical and regulatory, has plagued cellulosic biofuel production. Producing ethanol from cellulose requires extensive physical and chemical processing to break down indigestible molecules into sugars that are then converted into ethanol.¹⁹⁸ Notwithstanding technological advances, the process remains "complex, capital-intensive, and costly."¹⁹⁹ Currently, the primary method of producing cellulosic ethanol employs corn fiber left over from corn ethanol production as a feedstock.²⁰⁰ Existing corn ethanol facilities can be modified through "bolt-on" expansions to produce cellulosic ethanol in a comparatively economical manner.²⁰¹ However, producing cellulosic ethanol at statutorily mandated levels would require large stand-alone facilities dedicated to cellulosic ethanol.²⁰² Few such facilities exist, and they have required large capital investments far exceeding those of a conventional corn ethanol plant.²⁰³ As a general matter, facilities expected to

194. See KELSIE BRACMORT, CONG. RESEARCH SERV., THE RENEWABLE FUEL STANDARD (RFS): IN BRIEF at 8 (2016) [hereinafter CRS 2016]; CRS 2015, *supra* note 181, at 2.

195. See ACKRILL & KAY, *supra* note 192, at 83–84.

196. See U.S. GOV'T ACCOUNTABILITY OFFICE, GAO 17-108 at 17, RENEWABLE FUEL STANDARD: LOW EXPECTED PRODUCTION VOLUMES MAKE IT UNLIKELY THAT ADVANCED BIOFUELS CAN MEET INCREASING TARGETS (2016) [hereinafter GAO 17-108]. Cellulosic biofuel includes cellulosic ethanol, renewable gasoline, cellulosic diesel, and renewable natural gas from landfills. *See id.* at 5.

197. See CRS 2015, *supra* note 181, at 6; GAO 17-108, *supra* note 196, at 17.

198. See Peplow, *supra* note 189, at 152.

199. CONG. BUDGET OFFICE, THE RENEWABLE FUEL STANDARDS: ISSUES FOR 2014 AND BEYOND 2 (2014) [hereinafter CBO 2014].

200. See GAO 17-108, *supra* note 196, at 17.

201. *See id.*

202. *See id.*

203. See CBO 2014, *supra* note 199, at 2; CRS 2015, *supra* note 181, at 16. Renewable natural gas faces similar issues, as the processing of such gas for use as a transportation fuel is costly. GAO 17-108, *supra* note 196, at 17–18.

contribute significantly to cellulosic ethanol production have encountered financial and technical difficulties.²⁰⁴

On the regulatory side, the availability and frequent use of statutory waivers have created further uncertainty that has undermined the cellulosic ethanol market. Each year, the Environmental Protection Agency (EPA) may waive any of the RFS volume requirements if the agency determines that “there is an inadequate domestic supply” of a biofuel or if “implementation of the requirement would severely harm the economy or environment.”²⁰⁵ The volume requirements for cellulosic biofuel also may be reduced if projected production capacity is below mandated levels.²⁰⁶ These waiver provisions acknowledge the uncertainties of technology development and offer flexibility to respond to unanticipated circumstances.²⁰⁷ However, to issue a waiver, EPA must perform a number of complex tasks, such as determining whether actual production can satisfy statutory mandates, allocating mandated volume among regulated parties, and deciding how much credit to award to different kinds of biofuel.²⁰⁸

EPA has repeatedly issued waivers reducing the volume requirements for cellulosic biofuel and advanced biofuels.²⁰⁹ To justify the waivers, EPA has cited the slow development of the cellulosic biofuel industry and the limited supply of other advanced biofuels to offset the cellulosic biofuel shortfall.²¹⁰ The waivers for cellulosic biofuel have been particularly drastic: in each year since 2010, EPA has cut the required volume to a small fraction of the statutory amounts.²¹¹ Unfortunately, the frequent and sometimes belated waivers have fostered additional uncertainty for investors, producers, and feedstock growers in the cellulosic biofuel market.²¹² What rational actor would invest in, build, or commit to purchasing from a new biofuel production facility, when EPA is likely to reduce mandated biofuel amounts? Frequent legal challenges to EPA’s waiver determinations have only compounded the uncertainty.²¹³

204. See CRS 2015, *supra* note 181, at 7. Other advanced biofuels, such as algal biofuels and cellulosic renewable gasoline, have proven to be technologically sound yet economically uncompetitive with conventional gasoline at current prices. See GAO 17-108, *supra* note 196, at 18.

205. 42 U.S.C. § 7545(o)(7) (2012).

206. *Id.* § 7545(o)(7)(D) (2012).

207. See KELSI BRACMORT, CONGRESSIONAL RESEARCH SERVICE, THE RENEWABLE FUEL STANDARD (RFS): WAIVER AUTHORITY AND MODIFICATION OF VOLUMES at 6 (2017) [hereinafter CRS 2017].

208. See Powers, *supra* note 185, at 145–46.

209. See CRS 2017, *supra* note 207, at 5–6; CRS 2016, *supra* note 194, at 4–5.

210. See CRS 2017, *supra* note 207, at 5–6; CRS 2016, *supra* note 194, at 4–5.

211. See CRS 2017, *supra* note 207, at 5; CRS 2016, *supra* note 194, at 4–5.

212. See Powers, *supra* note 185, at 150; CRS 2015, *supra* note 181, at 13; CRS 2016, *supra* note 194, at 10; CRS 2017, *supra* note 207, at 6.

213. See Powers, *supra* note 185, at 139–50; CRS 2015, *supra* note 181, at 12–13. A further source of uncertainty for biofuel producers is the short-term nature of biofuel tax credits, which Congress has reinstated about every two years. U.S. GOV’T ACCOUNTABILITY OFF., GAO 17-94, RENEWABLE FUEL STANDARD: PROGRAM UNLIKELY TO MEET ITS TARGETS FOR REDUCING GREENHOUSE GAS EMISSIONS 15 (2016).

The political economy surrounding the second-generation RFS has proven especially difficult. In order to succeed, renewable fuels must displace fossil fuels backed by an entrenched industry. Not surprisingly, whereas first-generation biofuels, supported by agricultural interests, have achieved some commercial success,²¹⁴ second-generation biofuels have struggled in the face of attacks by oil producers and automobile manufacturers.²¹⁵ Biofuel use also has been stymied by the blend wall problem—an effective ceiling on the market for ethanol resulting from limitations on the percentage of ethanol that can be blended with conventional gasoline.²¹⁶

CDR technologies may not face resistance from powerful interests, nor a problem akin to the ethanol blend wall. Nonetheless, the analogy to biofuels illustrates some of the challenges CDR can expect to encounter. First, cellulosic biofuel technology was not ready for commercial deployment when Congress established the RFS, yet the RFS assumed the feasibility of a rapid and massive scale-up.²¹⁷ Successful use of CDR technologies likewise would require a leap from technologies still in the developmental stage to widespread deployment. Indeed, CDR deployment would have to occur on a global scale, and not just nationally.

In addition, mandating a technology, as the RFS does, has not been sufficient to bring about widespread use of advanced biofuels. Similarly, a mandate alone will not result in broad adoption of CDR. Technology-forcing mandates are more likely to be successful when “regulators can credibly commit to enforcing a standard” and “there is competitive pressure to develop new technologies.”²¹⁸ Repeated waivers of the cellulosic biofuel RFS have undermined its credibility and fostered an expectation of future waivers as well. For CDR, applying a technology-forcing mandate will be especially difficult, even if waivers are not available. The RFS was imposed on fuel blenders and could be enforced against them (at least in theory). In contrast, a technology-forcing mandate for CDR would have no obvious regulatory target on which a mandate could be imposed.

Furthermore, certifying that specific fuels meet the cellulosic biofuels RFS has forced EPA to grapple with various uncertainties associated with life-cycle analyses of GHG emissions.²¹⁹ These uncertainties involve crop yields, fertilizer use, changes in land use, fuel production efficiency, and other factors.²²⁰ Effective CDR deployment similarly will require accurate GHG life-cycle

214. See Lin, *supra* note 186, at 1830.

215. See Reitze, *supra* note 91, at 313, 317–19.

216. See CRS 2016, *supra* note 194, at 8.

217. See Powers, *supra* note 185, at 154.

218. David Gerard & Lester B. Lave, *Implementing Technology-Forcing Policies: The 1970 Clean Air Act Amendments and the Introduction of Advanced Automotive Emissions Controls in the United States*, 72 *TECH. FORECASTING & SOC. CHANGE* 761, 765 (2005).

219. See CBO 2014, *supra* note 199, at 6.

220. See *id.* at 21.

analyses—and the addressing of similar uncertainties. Analyses will be necessary not only to evaluate each CDR technique, but also to ensure that individual CDR operations actually remove GHGs.²²¹ Although the performance of these analyses may appear to be a purely technical endeavor, they are likely to be contested because of their economic and environmental implications.

Finally, coordinating the harvest, storage, and transport of feedstock for cellulosic biofuels, as well as the biofuels manufacturing process, has faced significant logistical difficulties.²²² In some instances, negotiating contracts to obtain feedstock from individual farmers has taken longer than constructing a biofuels plant.²²³ Most CDR techniques will face similar logistical challenges: for example, BECCS requires the cultivation, harvest, storage, and transport of bioenergy crops, production of bioenergy, and collection and sequestration of carbon.²²⁴ Implementation will require time and resources not only to put in place the necessary infrastructure, but also to make contractual arrangements, acquire property rights, and navigate the regulatory landscape.²²⁵

C. Carbon Capture and Storage

CCS, “a process consisting of the separation of CO₂ from industrial and energy-related sources, transport to a storage location, and long-term isolation from the atmosphere,” is a critical component of BECCS and DACS.²²⁶ The history of CCS development is of interest not only because of its implications for CDR techniques that incorporate it, but also as a case study in technology development.

CCS builds on technology used for over forty years in enhanced oil recovery—the injection of CO₂ into an oil field to increase production rather than to store carbon.²²⁷ Indeed, almost all large-scale CCS projects to date involve

221. Controversy regarding the use of U.S. wood pellets to fuel European power plants illustrates the importance of accurate GHG accounting. In the United States, logging activity for the purposes of wood pellet manufacture has skyrocketed in response to European policies designed to reduce coal burning. Whether such policies benefit the climate depends on the details: if the wood would otherwise be discarded, there is a climate benefit; but if large trees—particularly hardwoods—are used, the practice can increase GHG emissions. See Joby Warrick, *How Europe's Climate Policies Led to More U.S. Trees Being Cut Down*, WASH. POST (June 2, 2015), https://www.washingtonpost.com/national/health-science/how-europes-climate-policies-have-led-to-more-trees-cut-down-in-the-us/2015/06/01/ab1a2d9e-060e-11e5-bc72-f3e16bf50bb6_story.html?noredirect=on&utm_term=.763a46797f35; Warren Cornwall, *The Burning Question*, 355 SCIENCE 18, 18–21 (2017).

222. See CBO 2014, *supra* note 199, at 7.

223. See GAO 17-108, *supra* note 196, at 22.

224. See Part I.A.1.

225. Cf. Wendy B. Jacobs, *Carbon Capture and Sequestration*, in GLOBAL CLIMATE CHANGE AND U.S. LAW 581–602 (Michael B. Gerrard & Jody Freeman eds., 2d ed. 2014) (identifying U.S. legal issues associated with carbon capture and sequestration).

226. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CARBON DIOXIDE CAPTURE AND STORAGE 3 (2005) [hereinafter IPCC REPORT]. By itself, CCS is not classified as CDR because it does not remove CO₂ that is already in the atmosphere. WG1AR5, *supra* note 16, at 546.

227. See Arnold W. Reitze Jr., *Carbon Capture and Storage (Sequestration)*, 43 ENVTL. L. RPT. NEWS & ANALYSIS 10414, 10414 (2014).

enhanced oil recovery;²²⁸ while carbon storage can offer additional revenue, these projects often are not designed to provide for long-term or large-scale carbon storage.²²⁹ CCS has received serious consideration as a climate policy response since at least 2005, when the Intergovernmental Panel on Climate Change issued a special report devoted to the subject.²³⁰

CCS nonetheless remains “technically immature . . . in terms of integrating capture, transport and storage in full-scale projects.”²³¹ Challenges to scaling up CCS include developing efficient means of capturing CO₂, identifying reliable storage sites, and establishing pipeline networks.²³² CCS projects are complex and expensive, requiring large capital investments and imposing substantial operating costs, and they involve significant technological, financial, and reputational risks.²³³ Although the first large-scale project dedicated to CO₂ storage commenced operations in 1996, that project captured CO₂ from natural gas reservoirs rather than from the atmosphere.²³⁴ Demonstration-scale projects and further research remain necessary to refine the technology and bring down the costs of capturing CO₂ from the atmosphere and storing it.²³⁵ A 2016 report found that globally, “the pace of CCS deployment has fallen far short of initial expectations,” and the pipeline of new large-scale CCS projects has shrunk by half since 2010.²³⁶

Economically, CCS makes little sense in the absence of policies requiring the costs of carbon pollution to be internalized. Even in jurisdictions that have imposed a price on carbon, incentives have not been sufficiently strong to bring about CCS adoption.²³⁷ CCS is expensive compared to other means of reducing carbon emissions, as significant amounts of energy are needed to extract CO₂ from power plant or industrial waste streams and compress it into a liquid.²³⁸ In the United States, demonstration projects, tax credits, and regulatory policies

228. See Ronald Wennersten et al., *The Future Potential for Carbon Capture and Storage in Climate Change Mitigation—An Overview from Perspectives of Technology, Economy, and Risk*, 103 J. CLEANER PROD. 724, 729 (2015).

229. See Dennis Y.C. Leung et al., *An Overview of Current Status of Carbon Dioxide Capture and Storage Technologies*, 39 RENEWABLE & SUSTAINABLE ENERGY REV. 426, 437 (2014); INTERNATIONAL ENERGY AGENCY, TECHNOLOGY ROADMAP: CARBON CAPTURE AND STORAGE 20 (2013) [hereinafter IEA 2013]; INTERNATIONAL ENERGY AGENCY, A POLICY STRATEGY FOR CARBON CAPTURE AND STORAGE 33 (2012) [hereinafter IEA 2012].

230. See IPCC REPORT, *supra* note 226.

231. IEA 2012, *supra* note 229, at 8.

232. See Leung et al., *supra* note 229, at 437–38; IEA 2013, *supra* note 229, at 25–35.

233. See Florian Kern et al., *The Political Economy of Carbon Capture and Storage: An Analysis of Two Demonstration Projects*, 102 TECH. FORECASTING & SOC. CHANGE 250, 251 (2016).

234. See IEA 2016, *supra* note 105, at 19–21 (discussing Norway’s Sleipner project).

235. See IEA 2013, *supra* note 229, at 9; Kern et al., *supra* note 233, at 250–51.

236. IEA 2016, *supra* note 105, at 11, 14.

237. See Wennersten et al., *supra* note 228, at 731 (“Economically, CCS is still expensive compared with doing nothing”); see also CONG. BUDGET OFFICE, FEDERAL EFFORTS TO REDUCE THE COST OF CAPTURING AND STORING CARBON DIOXIDE 4 (2012) [hereinafter CBO 2012] (noting that several demonstration projects were canceled as cap-and-trade regulation of carbon emissions became less likely).

238. See CBO 2012, *supra* note 237, at 2.

have not been adequate to prompt widespread CCS use. The Department of Energy has supported research and development (R&D) and CCS demonstration projects at electricity generating power plants.²³⁹ A tax credit is available for CCS projects that capture and store CO₂ from industrial sources.²⁴⁰ In addition, regulations limiting carbon emissions from new or modified power plants allow for the construction of coal-fired plants if they incorporate CCS.²⁴¹ However, these regulations have stimulated very little construction of coal-fired units combined with CCS.²⁴² The relatively low cost of natural gas, combined with the high cost of CCS, has led to the construction of natural gas-fired units instead.²⁴³ In theory, CCS also could be installed on natural gas-fired units, but because these units generate lesser amounts of CO₂, the per-unit costs of carbon capture would be even higher than for coal-fired units.²⁴⁴

Legal obstacles and uncertainties associated with the transport and storage of CO₂, including liability concerns, also have hindered CCS implementation.²⁴⁵ Members of the public have expressed concerns that CO₂ might leak from storage sites and cause adverse health and environmental effects.²⁴⁶ Also prompting opposition in some quarters is CCS's association with "clean coal"—a concern that might also undermine support for CDR.²⁴⁷

The overlap between CCS and some types of CDR suggests that measures to facilitate widespread CCS use would also lay the groundwork for CDR. Imposing a sufficiently high price on carbon would send a signal to industry, investors, and other actors of the value of CCS and CDR. Targeted and

239. See Arnold W. Reitze Jr., *Federal Control of Carbon Capture and Storage*, 41 ENVTL. L. RPTR. NEWS & ANALYSIS 10796, 10822–23 (2011); see also CBO 2012, *supra* note 237, at 1 (estimating that Congress provided \$6.9 billion to support CCS technology development between 2005 and 2012).

240. This tax credit is set to expire once a ceiling is reached. I.R.C. § 45Q, added by the Energy Improvement and Extension Act of 2008, Pub. L. No. 110-343, § 115(a). A tax credit relating to EOR also may apply to some CCS projects. 26 U.S.C. § 43 (2012).

241. See DAVID R. WOOLEY & ELIZABETH M. MORSS, CLEAN AIR ACT HANDBOOK § 4.4 New Source Performance Standards (Sept. 2016 update).

242. See Reitze, *supra* note 227, at 10415.

243. See *id.* at 10416–17; see, e.g., Kristi E. Swartz, *Kemper's Officially a Gas Plant. What Comes Next?*, ENERGYWIRE (July 7, 2017), <https://www.eenews.net/energywire/stories/1060057035?t=https%3A%2F%2Fwww.eenews.net%2Fstories%2F1060057035> (discussing utility's decision to operate facility as a natural gas plant rather than as a plant that would gasify lignite coal and capture most of its carbon emissions). Even with strong policy support, coal-fired power plants with CCS are unlikely to achieve commercial viability. Currently, electricity from a new coal plant costs more than electricity generated from new wind or solar sources. See Jeffrey Rissman & Robbie Orvis, *Carbon Capture and Storage: An Expensive Option for Reducing U.S. CO₂ Emissions*, FORBES (May 3, 2017), <https://www.forbes.com/sites/energyinnovation/2017/05/03/carbon-capture-and-storage-an-expensive-option-for-reducing-u-s-co2-emissions/#7938ed376482>. Adding CCS to new coal-fired facilities would only make them less competitive.

244. See David E. Adelman, *Confronting the Bleak Economics of CCS in the United States*, at 5, in CARBON CAPTURE AND STORAGE—EMERGING ISSUES OF LAW AND REGULATION (Ian Havercroft et al. eds., 2d ed. 2017 forthcoming), <https://ssrn.com/abstract=3036613>.

245. See Leung et al., *supra* note 229, at 437; Jacobs, *supra* note 225, at 585–601 (discussing legal issues).

246. See Wennersten et al., *supra* note 228, at 732.

247. See IEA 2016, *supra* note 105, at 50.

augmented financial support—whether in the form of capital grants, tax credits, feed-in tariffs, and loan guarantees—also could advance the technology.²⁴⁸ Research to bring down costs appears to be especially critical, and the Congressional Budget Office has recommended that the federal government steer its resources away from more costly demonstration projects and concentrate on R&D.²⁴⁹ Whatever policy measures are adopted, long-term commitment and stability is essential, particularly when nearly a decade can pass between funding commitments and project operation.²⁵⁰ CCS is “uniquely dependent on the degree of climate policy ambition” because it provides few benefits other than emissions reduction²⁵¹—a characterization that applies equally well to CDR technologies.

IV. DEVELOPING A CDR POLICY

Having considered forest-related emissions, the RFS, and CCS as case studies in combating climate change through technology development and adoption, we can turn our attention back to CDR. What might these efforts to stimulate other technologies—and their relative lack of success—suggest about implementing CDR on the scale assumed under the Paris Agreement?

A. *Why Not Wait and See?*

Forbearance in implementing CDR may appear to be a logical course, especially in light of the immature state of CDR technologies and the potential complexities involved. Broad scale implementation of CDR surely will require policy incentives, whether in the form of a carbon tax, carbon credits, or direct mandates. A global CDR strategy will also need accounting systems to track carbon reductions, monitoring and verification schemes to ensure that claimed reductions are real, regulation of CDR projects to address adverse effects, and liability regimes to deal with unintended releases.²⁵² A plausible response to these implementation challenges would be to hold off on determining the details of these regimes until we learn more about each technique and decide on which, if any, to implement.²⁵³ Such a “wait and see” approach would be consistent with models that assume deployment of CDR several decades from now.²⁵⁴ It would

248. *See id.* at 11, 39–41, 71.

249. *See* CBO 2012, *supra* note 237, at 5, 14; *see also* Adelman, *supra* note 244, at 9 (urging investment in fundamental research and development rather than “deployment of CCS technologies that have little prospect of ever being economically competitive”).

250. *See* IEA 2016, *supra* note 105, at 46, 72.

251. *Id.* at 69–70.

252. *Cf.* Meadowcroft, *supra* note 8, at 144 (contending that integration of CDR activities would require mechanisms to verify CO₂ flows, ensure long-term carbon sequestration, and address collateral damage).

253. *Cf.* Lomax et al., *Reframing*, *supra* note 17, at 132 (noting possible rationales supporting the view that CDR technologies “are solely a concern for the future”).

254. *See id.* at 129.

avoid diverting attention and resources away from the urgent task of reducing GHG emissions.²⁵⁵ And it would reduce the danger of locking in unproven technologies that could turn out to be technologically infeasible, financially burdensome, or socially unacceptable.

However, deferring CDR policy development could lead to missed “near-term opportunities to develop greenhouse gas sinks at relatively low costs.”²⁵⁶ As discussed above, the existing climate regime already has incorporated mechanisms to account for the climate benefits of afforestation, reforestation, and better forest management.²⁵⁷ Refining these mechanisms and considering their potential application to CDR pilot projects could yield climate benefits while advancing CDR policy development.²⁵⁸ Sufficient evidence that a CDR technique is effective and has minimal or manageable side effects could warrant integration of the technique into the international climate regime.

More importantly, a “wait and see” approach to CDR policy turns a blind eye to the tremendous gap between the immature state of CDR technologies today and the global-scale CDR implementation assumed in the Paris Agreement.²⁵⁹ Climate policy modeling that incorporates CDR deployment hinges on unrealistic assumptions about technological certainty, geopolitical stability, social acceptance, and various other factors.²⁶⁰ Experience with REDD+, the RFS, and CCS underscores the difficulty of bringing analogous technologies to maturity and deploying them widely. It can take decades to achieve technical breakthroughs, establish necessary infrastructures, and put in place supporting laws and policies. Admittedly, a CDR policy may seem premature at a time when most CDR techniques are in the early stages of research and involve multiple unknowns.²⁶¹ Nonetheless, today’s policies—or their absence—will affect the prospects for successful development and deployment of CDR. A “wait and see” approach would offer little incentive to develop CDR technologies, research uncertainties surrounding those technologies, or establish business models for CDR deployment.²⁶² In the absence of adequate information regarding a particular CDR technique’s technical feasibility, effectiveness, scalability, or risks, the global community will be unable to make informed decisions on how to proceed.

Successful deployment is not assured even if researchers perfect CDR technologies and generate sufficient information for society to make sound decisions regarding their adoption. Large-scale deployment will require

255. See Fuss et al., *Betting*, *supra* note 10, at 850.

256. Lomax et al., *Reframing*, *supra* note 17, at 132.

257. See *infra* Part III.A.

258. See Lomax et al., *Reframing*, *supra* note 17, at 131–32; see Boysen et al., *supra* note 36, at 471–72 (concluding that terrestrial CDR is a limited tool for combating climate change but urging nonetheless that efforts be “started and deployed immediately” to complement ongoing mitigation).

259. See Vaughan & Gough, WPD 1b, *supra* note 19, at 25.

260. See Peters & Geden, *supra* note 125, at 620.

261. See Meadowcroft, *supra* note 8, at 143.

262. See Lomax et al., *Reframing*, *supra* note 17, at 132.

supporting infrastructure, technologies, and institutions—elements that are unlikely to be established under a “wait and see” approach.²⁶³ The infrastructure necessary to implement BECCS, for example, includes broad swaths of land for bioenergy production, mechanisms to transport large quantities of biomass, power generation systems that can operate solely or primarily on biomass, an extensive network of pipelines to transport CO₂ from capture to storage, and sizeable subsurface carbon storage facilities.²⁶⁴ These infrastructure requirements are not insignificant: one estimate suggests that a “roll out [of BECCS could take] over a period of 14 and 600 years to attain the capacity to remove 1 [part per million] [of CO₂] from the atmosphere.”²⁶⁵ Moreover, because the various components of a single BECCS project may be located in different countries, successful implementation could require the coordination and harmonization of national policies.²⁶⁶

In short, between the carbon-intensive present and a negative-carbon future lie critical gaps in technology, information, and supporting infrastructure. Unfortunately, these gaps are only exacerbated by the Paris Agreement’s heavy yet unspoken reliance on CDR to attain the 2°C or 1.5°C outcomes. This reliance—whether deliberate or not—potentially locks the international community into deploying CDR in the future by allowing relatively weak emissions reduction efforts to continue. The international community should not pretend that the 2C goal can be achieved without far more drastic emissions reductions or widespread CDR. Openly acknowledging CDR’s likely prominent role will surface the difficult choices to be made and facilitate efforts to begin to address the gaps. The following discussion suggests concrete steps for addressing the disconnect between Paris’s underlying assumptions and the lagging public and policy discourse on CDR.

B. A Learning-By-Doing Approach—with Guardrails

The contingent nature of future technology and the formidable barriers to scaling up CDR argue for an approach to “start learning by doing.”²⁶⁷ Rather than waiting for more information before proceeding, learning by doing

263. See *id.* (discussing risk of technological “lock-out”—that infrastructure, practices, and institutions will evolve so as to obstruct CDR scale-up efforts).

264. See Gough & Vaughan, WPD 1a, *supra* note 19, at 15–22; see also Fuss et al., *Research Priorities*, *supra* note 13, at 6 (estimating need for transportation network similar in size to current natural gas network).

265. Niall McGlashan et al., *High-Level Techno-Economic Assessment of Negative Emissions Technologies*, 90 *PROCESS SAFETY & ENVTL. PROT.* 501, 506 (2012); see also Vaughan & Gough, WPD 1b, *supra* note 19, at 24 (describing the scale at which models assume BECCS to be deployed as “extremely ambitious” and assumed timescale of deployment as “equally optimistic”).

266. See Peters & Geden, *supra* note 125, at 620–21 (discussing hypothetical BECCS project in which biomass harvested in Cameroon is exported to the United Kingdom for combustion and CO₂ capture, and CO₂ is then exported to Norway for storage).

267. Guy Lomax et al., *Investing in Negative Emissions*, 5 *NATURE CLIMATE CHANGE* 498, 499 (2015).

recognizes that inaction itself can have consequences and that well-planned action designed to generate information can enable better decision making.²⁶⁸ Inaction on CDR could be costly because scaling up CDR will require a long lead time, and climate change's impacts will only grow with the passage of time. Learning by doing can reduce the numerous uncertainties surrounding CDR.

In the context of technology development, learning by doing refers to "experience that may be obtained in the employment of a certain technology through its practical use."²⁶⁹ The benefits of learning by doing include increased proficiency, cost reductions, and institutional transformations necessary for widespread technology adoption.²⁷⁰ While the desirability of increased proficiency and cost reductions may be obvious, the importance of institutional mechanisms to support technology diffusion should not be underestimated. For example, widespread adoption of photovoltaic solar technologies occurred only after third-party ownership structures, solar loan products, and other creative financing mechanisms were developed to complement technical advances.²⁷¹ Supportive policies such as feed-in tariffs and renewable portfolio standards also have been essential in generally fostering the deployment of renewable energy technologies.²⁷² A learning by doing approach could be beneficial in deciding whether and how to proceed with the similarly complex field of CDR.

Doing too much to advance CDR now, however, might lock in technological choices that could prove regrettable. Ideally, policy makers would acquire enough information to assess the ability of each type of CDR to combat climate change effectively, but would also preserve the ability to make decisions on CDR based on future assessments. Balancing these competing objectives will be difficult. The development and adoption of technologies is a path-dependent process, and early advantages enjoyed by a particular technology can enable its subsequent dominance.²⁷³ Learning by doing can refine a technology and reduce its implementation costs, but these benefits, along with increasing returns from that technology's widespread adoption, can lock in that technology and leave alternative technologies at a disadvantage.²⁷⁴

The phenomenon of technological lock-in has social and cognitive dimensions as well. Socially, the sunk costs involved in developing an extensive

268. See Holly Doremus, *Precaution, Science, and Learning While Doing in Natural Resource Management*, 82 WASH. L. REV. 547, 554–55 (2007) (discussing "learning while doing" in context of natural resource management).

269. Ambuj D. Sagar & Bob van der Zwaan, *Technological Innovation in the Energy Sector: R&D, Deployment, and Learning-by-Doing*, 34 ENERGY POL'Y 2601, 2604 (2006).

270. See *id.* at 2602, 2605.

271. See MARK BOLINGER & EDWARD HOLT, ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY, A SURVEY OF STATE AND LOCAL PV PROGRAM RESPONSE TO FINANCIAL INNOVATION AND DISPARATE FEDERAL TAX TREATMENT IN THE RESIDENTIAL PV SECTOR 1, 4–10 (2015).

272. See Felix Mormann, *Clean Energy Federalism*, 67 FLA. L. REV. 1621, 1630–32 (2015).

273. See Rose C. Cairns, *Climate Geoengineering: Issues of Path-Dependence and Socio-Technical Lock-In*, 5 WIRES CLIMATE CHANGE 649, 650–51 (2014).

274. See *id.* at 650.

infrastructure to support a technology can “create vested interests in keeping facilities operational.”²⁷⁵ Cognitively, the framing of a problem and possible solutions can influence society’s assessment of alternative courses of action.²⁷⁶ These various dimensions of lock-in suggest the need to avoid premature commitments to specific technologies while advancing CDR efforts in general.

The risk of technological lock-in depends on various factors, including infrastructure requirements, longevity of capital assets, and early advantages. Complex and extensive infrastructure requirements favor lock-in because they serve as barriers to entry for rival technologies, and they foster the growth of interests vested in keeping existing infrastructure in use.²⁷⁷ Long-lived capital assets reduce opportunities to substitute new technologies for existing ones.²⁷⁸ And a particular technology’s early advantages can lead to greater experimentation and use of that technology, thereby facilitating further improvements and cost reductions.²⁷⁹

Some CDR techniques, including BECCS, have features suggesting a substantial lock-in danger. BECCS would require an extensive network of land, facilities, pipelines, and equipment to cultivate, harvest, and transport bioenergy crops, produce bioenergy, and collect and sequester carbon.²⁸⁰ The capital assets involved in this infrastructure would generally be long-lived.²⁸¹ And BECCS in particular is poised to benefit from its leading position among CDR proposals.²⁸² Granted, neither BECCS nor any other CDR technology will be widely adopted without direct mandates, subsidies, carbon credits, or other policy interventions.²⁸³ The need for policy support may somewhat mitigate the danger of lock-in. In theory, policies could be fine-tuned or changed to account for updated information on the efficacy or risks of a particular CDR technique. However, extensive policy support for BECCS at an early stage could build up vested interests that might obstruct subsequent policy change.

C. Constructing a CDR Policy

Recognizing the need to integrate CDR into mainstream climate policy, Guy Lomax and his colleagues have suggested four “principles” for CDR policy:

275. *Id.* at 651.

276. *See id.* at 651–52; Rob Bellamy et al., *A Review of Climate Geoengineering Appraisals*, 3 WIREs CLIMATE CHANGE 597, 610–11 (2012).

277. *See* Cairns, *supra* note 273, at 651; Albert C. Lin, *The Missing Pieces of Geoengineering Research Governance*, 100 MINN. L. REV. 2509, 2542 (2016).

278. *See* Ivan Scrase & Gordon MacKerron, *Lock-In*, in *ENERGY FOR THE FUTURE: A NEW AGENDA* 89, 95 (Ivan Scrase & Gordon MacKerron eds., 2009).

279. *See* Lin, *supra* note 277, at 2541.

280. *See supra* text accompanying notes 264–265.

281. *Cf.* Lin, *supra* note 186, at 1820 (noting that energy systems generally rely on extensive and long-lived infrastructure that turns over slowly).

282. *See supra* Part I.A.1.

283. *Cf. supra* Part III.C (discussing how CCS makes little economic sense in the absence of policies requiring costs of carbon pollution to be internalized).

supporting research, development, and demonstration of promising approaches; supporting deployment of promising near-term opportunities; integrating CDR into emissions accounting and climate policy frameworks; and building system flexibility to lay the groundwork for future CDR.²⁸⁴ Although characterized as “principles,” these suggestions are more accurately described as general policy prescriptions. Using these general prescriptions as a starting point, the following discussion first identifies objectives to guide future actions on CDR and then recommends specific policy measures that advance those objectives. Note that while CDR policy may be adopted at a global level—through decisions made under the Framework Convention regime, for example—that policy is likely to be fleshed out and implemented through national governments.²⁸⁵

What should be the objectives of CDR policy? As earlier Parts of this Article have explained, uncertainty surrounds CDR techniques, and the international community has sidestepped any policy commitment to CDR. At the same time, a policy commitment to CDR—or at least CDR development—appears increasingly necessary. These circumstances argue for adopting the following objectives for CDR policy: enabling learning opportunities, advancing policy dialogue, undertaking no-regrets measures, and avoiding lock-in. First, because gathering information about CDR techniques and their risks is essential to deciding whether and how to proceed, CDR policy should promote learning and encourage the development of such information. Second, public awareness of CDR is low, and policymakers generally have not addressed or acknowledged its potentially significant role. To achieve the objective of mainstreaming CDR into climate change discussions, CDR policy should include measures that raise public awareness and advance public dialogue on CDR among policymakers. Third, moving forward with CDR R&D will require substantial resources, without any guarantee of success. However, a prudent, no-regrets approach might include investments that could advance CDR efforts as well as other societal objectives. Finally, at least some CDR technologies present a significant lock-in danger. Maintaining a diverse range of climate change response options, particularly at this early stage in CDR development, can help to counter that danger.²⁸⁶

Policy measures that would advance the foregoing objectives include: supporting research on a range of CDR techniques, fostering disclosure and transparency regarding CDR’s potential role, developing an interim status provisionally recognizing the climate change benefits of certain CDR projects, investing in development of carbon storage, establishing accounting protocols for CDR, and instituting carbon pricing mechanisms. Much of this work, particularly with respect to disclosure and interim status, would benefit from

284. See Lomax et al., *Reframing*, *supra* note 17, at 133.

285. Cf. Peters & Geden, *supra* note 125, at 619 (characterizing discussions of CDR at the global level as “an unhelpful abstraction” and focusing instead on the differing positions that developing and industrialized countries might take on CDR).

286. See Cairns, *supra* note 273, at 651.

international efforts that would build upon the Paris Agreement. However, national and subnational governments would have an indispensable role in developing and implementing these policies as well.

1. Research

Providing more support for CDR R&D is a straightforward way to enable learning and advance policy dialogue.²⁸⁷ Undoubtedly, the immature state of CDR techniques warrants greater funding for research.²⁸⁸ Pilot and demonstration projects can advance not only technical knowledge, but also policy development and learning.²⁸⁹ Research on a range of CDR techniques as well as barriers to development would build up a broad knowledge base and guard against technological lock-in.²⁹⁰

As experience with CCS illustrates, putting a price on carbon can create a positive environment for technology research and development, but may be insufficient to make a technology commercially viable.²⁹¹ More targeted forms of support may be necessary.²⁹² For example, a concentrated effort focused on CDR technologies, housed within or patterned after the Department of Energy's ARPA-E program, could give a critical boost to laboratory concepts that might not otherwise receive research funding.²⁹³ Regardless of the particular policy tools chosen, the long-term and policy-dependent nature of CDR projects makes it essential that support for CDR be stable.²⁹⁴

Support for research could come from the public or private sector. Although the Trump Administration has been dismissive of scientific research generally

287. Cf. Lomax et al., *Investing*, *supra* note 267, at 498 (“[a] natural, scientific response is to call for a substantial interdisciplinary research agenda to explore and try to constrain the uncertainties . . .”).

288. See NAS CDR, *supra* note 7, at 90–91 (recommending expanded U.S. research effort on a variety of CDR techniques); Lomax et al., *Reframing*, *supra* note 17, at 133.

289. See Meadowcroft, *supra* note 8, at 144–45; see also McGlashan et al., *supra* note 265, at 508 (recommending establishment of demonstration facilities for CCS as an important step in developing BECCS).

290. See Fuss et al., *Betting*, *supra* note 10, at 852.

291. See *supra* Part III.C.

292. See IEA 2012, *supra* note 229, at 9–11, 11 n.4.

293. The mission of the ARPA-E (“Advanced Research Projects Agency-Energy”) program is “to overcome the long-term and high-risk technology barriers in the development of energy technologies.” 42 U.S.C. § 16538(b) (2012). ARPA-E, which operates with significant autonomy, is tasked “with funding high-risk, potentially high-return research, to translate scientific discoveries and cutting-edge inventions into technological innovations,” and is “free to support research into any type of technology or fuel that supports its mission.” NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE, AN ASSESSMENT OF ARPA-E 22 (2017). The program supports “proof-of-concept” projects as well as projects “intended to develop technology from ideas to laboratory-scale prototypes” through grants averaging \$2.7 million, with the aim that successful projects will attract funding for commercialization from private investors and other sources. *Id.* at 40, 42.

294. See IEA 2012, *supra* note 229, at 12 (noting that investors “are particularly sensitive to policy risk when assets (such as CCS) are long-lived and heavily dependent on policy support”); cf. Joshua D. Sarnoff, *Government Choices in Innovation Funding (with Reference to Climate Change)*, 62 EMORY L.J. 1087, 1111 (2013) (noting that “predictable, long-term funding will permit greater experimentation with alternative research pathways” for energy innovation).

and climate change research specifically,²⁹⁵ geoengineering research has attracted bipartisan interest in Congress. There is incipient support for proposed legislation that would develop a research agenda for solar geoengineering (but not CDR).²⁹⁶ In addition, a November 2017 congressional subcommittee hearing focused on geoengineering.²⁹⁷

R&D can illuminate the extent to which any CDR technique offers a truly viable option for combating climate change.²⁹⁸ In a plausible future scenario, we might find CDR to be flawed but necessary: flawed because of limited effectiveness, high costs, and/or adverse consequences, yet necessary because cumulative GHG emissions may leave no better options for responding to climate change. Even under such a scenario, the information generated through CDR research could guide choices among CDR technologies, identify tradeoffs, and suggest ways to mitigate adverse effects.²⁹⁹ Under another possible scenario, research findings could lead to the sobering conclusion that CDR is so ineffective or problematic that exceeding the 2°C threshold instead might be preferable, or that solar geoengineering methods might merit serious consideration.

Although further CDR research would be valuable, it cannot resolve all uncertainties. Scenarios that incorporate CDR typically assume extensive timeframes spanning decades or even centuries; these timeframes exceed our capacity to anticipate technological, societal, cultural, and environmental changes.³⁰⁰ Furthermore, much of the desired information about CDR techniques does not involve objective and inherent truths. Rather, data concerning technical details, costs, and risks are contingent on today's decisions and actions.³⁰¹ The costs of implementing a particular CDR technique, for example, will depend not just on its inherent properties, but also on "public and private investment decisions, policy choices and regulatory frameworks, operational experiences (reliability, accidents, etc.), and public attitudes and political struggles."³⁰² In the end, deciding whether and how to deploy CDR will involve value-based judgments that research can inform but not answer.

295. See Scott Waldman, *Here's How Science Fared in the First Year of Trump*, E&E NEWS (Dec. 20, 2017), <https://www.eenews.net/climatewire/stories/1060069521>.

296. Geoengineering Research Evaluation Act of 2017, H.R. 4586, 115th Cong. (introduced by Rep. McNerney on Dec. 7, 2017); Arianna Skibell, *Lamar Smith Urges Action Through Technology*, E&E NEWS (Jan. 29, 2018), <https://www.eenews.net/eenewspm/stories/1060072263>.

297. Arianna Skibell, *Lawmakers Set Partisan Brawls Aside to Discuss Geoengineering*, E&E NEWS (Nov. 9, 2017), <https://www.eenews.net/stories/1060066081>.

298. Cf. Field & Mach, *supra* note 13, at 707 (advocating the "rightsizing" of CDR to "avoid[] reckless assumptions that massive-scale CDR with low costs and limited side effects will quickly materialize").

299. See Lomax et al., *Reframing, supra* note 17, at 133; see also Wil Burns & Simon Nicholson, *Bioenergy and Carbon Capture and Storage (BECCS): The Prospects and Challenges of an Emerging Climate Policy Response*, 7 J. ENVIRON. STUD. SCI. 527, 527 (2017) (urging robust assessment of sustainability and equity of BECCS projects).

300. See Meadowcroft, *supra* note 8, at 145.

301. See *id.* at 145–47.

302. *Id.* at 146.

2. Disclosure

Another straightforward but vital measure that would advance the public and policy dialogue on CDR is disclosure. Although integrated-assessment-modeling efforts explicitly assume the use of CDR, policymakers and the public have been slow to grasp its role in achieving the Paris Agreement's objective.³⁰³ Obscuring CDR's role may not be entirely accidental; one commentary even suggests that CDR "licenses the ongoing combustion of fossil fuels while ostensibly fulfilling the Paris commitments."³⁰⁴

Unfortunately, silence on CDR could prove to be a critical mistake. Thanks to its social and environmental ramifications, widespread CDR deployment will require public support to succeed. Failure to inform the public, undertake outreach efforts, and obtain public backing will imperil efforts to deploy CDR broadly. Mainstreaming CDR through efforts at greater transparency would lay the groundwork for CDR deployment, should CDR prove necessary. Mainstreaming CDR is essential for other reasons as well. It would provide a signal to markets, investors, and researchers that CDR efforts warrant time, money, and resources. It would jump-start needed conversations among and within governments regarding how CDR might take place on the ground. It could bolster support for direct mitigation of GHG emissions as the public and policymakers learn of the uncertainties and difficulties associated with CDR.³⁰⁵ And transparency on CDR would guard against technological lock-in by spurring debate on whether CDR or a specific CDR technique is appropriate.

What might greater transparency look like? An important first step in disclosure would be a formal and explicit acknowledgement that limiting global mean temperature rise to 2°C likely will require substantial reliance on CDR. Such acknowledgment might occur through an amendment to the Paris Agreement or through a decision adopted by the Conference of the Parties to the Framework Convention.³⁰⁶ Indeed, the Paris Agreement's global stocktake mechanism, which requires a periodic assessment of collective progress towards achieving the agreement's objectives, offers an opportunity to articulate the extent to which CDR might be needed to achieve the 2C goal.³⁰⁷ Further

303. See Oliver Geden, *The Paris Agreement and the Inherent Inconsistency of Climate Policymaking*, 7 WIREs CLIMATE CHANGE 790, 795 (2016); Anderson & Peters, *supra* note 2, at 182.

304. Anderson & Peters, *supra* note 2, at 183 (criticizing specifically reliance on the "highly speculative technology" of BECCS).

305. Cf. Geden, *supra* note 303, at 794 ("A strategic discussion of how to use CDR within a broader portfolio of climate policy measures has still not taken place.").

306. The IPCC's Fifth Assessment Report acknowledges that CDR will be necessary to meet ambitious climate targets. See, e.g., WG3AR5, *supra* note 23, at 10, 12. The incorporation of CDR into the IPCC report was hardly accidental. Pressured by climate policymakers to derive mitigation scenarios that would limit warming to 2°C, and "[f]aced with the problem that [IAM] models had very few credible scenarios that achieved 2C with emissions cuts alone," climate economists incorporated CO₂ removal as a "*deus ex machina*" to produce such scenarios. Andy Parker & Oliver Geden, *No Fudging on Geoengineering*, 9 NATURE GEOSCIENCE 859, 859–60 (2016).

307. Paris Agreement, *supra* note 105, at art. 14.

mainstreaming of CDR might occur through Framework Convention working group documents, national-level legislation, or policy reports. For example, the Intergovernmental Panel on Climate Change is scheduled to release in 2018 a report on possible GHG emission pathways for avoiding a temperature rise exceeding 1.5°C.³⁰⁸ That report should carefully assess the potential role of CDR. Additionally, individual countries might identify contemplated CDR projects as they revise their NDCs.

Disclosure and transparency can go beyond acknowledging CDR's likely importance. Policymakers could begin to clarify the permissibility—or impermissibility—of different types of CDR under international law.³⁰⁹ As noted above, CDR might fall within language in the Framework Convention and Paris Agreement referring to the “enhancement of sinks” as acceptable means of mitigation. Whether CDR would be an acceptable means of satisfying a country's NDC has yet to be tested. However, silence on CDR and the continuing ambiguity as to whether CDR qualifies as a form of mitigation suggest a deep-seated discomfort with the concept in official circles.³¹⁰ The resulting legal uncertainty discourages planning and investment in CDR.³¹¹ Further clouding the legal status of CDR, the international legal regime associated with the Convention on Biological Diversity has adopted a skeptical stance toward CDR. A 2011 Biodiversity Convention decision defined geoengineering to include “carbon sequestration from the atmosphere on a large scale that may affect biodiversity [excluding CCS],” and urged that no “climate-related geoengineering activities that may affect biodiversity” take place in the absence of adequate scientific justification for such activities and appropriate consideration of risks.³¹²

3. *Interim Status*

How should international legal regimes treat CDR? On the one hand, the Convention on Biological Diversity's cautious approach discourages CDR development. On the other hand, categorizing CDR as an acceptable type of mitigation under the international climate change regime could have the opposite effect. Even if CDR is treated as a legally permitted form of mitigation, however,

308. Decision IPCC/XLIV-4, Sixth Assessment Report (AR6) Products, Outline of the Special Report on 1.5C, at 3, http://www.ipcc.ch/meetings/session44/12_adopted_outline_sr15.pdf (listing “negative emission methodologies” as a climate response option to be assessed).

309. See Williamson, *supra* note 21, at 155.

310. See *id.* (noting that “mitigation and geoengineering have very different psychological connotations,” with the latter “frequently elicit[ing] suspicion”).

311. See generally Gary E. Marchant, *Sustainable Energy Technologies: Ten Lessons from the History of Technology Regulation*, 18 WIDENER L.J. 831, 848 (2009) (“the long-term stability and predictability of regulatory and other technology-promoting policies are important for providing the certainty needed for investment in and planning of new technologies”).

312. Report of the Tenth Meeting of the Conference of the Parties to the Convention on Biological Diversity, *Decision X/33: Biodiversity and Climate Change*, § 8(w) & footnote, UNEP/CBD/COP/10/27 (Jan. 20, 2011), <http://www.cbd.int/cop10/doc/>.

cost considerations likely will lead countries to opt for conventional mitigation rather than CDR in their NDCs. Private actors faced with carbon pricing requirements will do likewise.³¹³ Cost considerations aside, there are good reasons for the international climate change regime to treat CDR less favorably than conventional mitigation. CDR's effectiveness is uncertain, adverse consequences could be prohibitive, and the international community is far from ready to commit to CDR generally or to any specific CDR technique.

Treating CDR simply as a form of mitigation could bring into conflict the objectives of gathering information, developing the technologies, and avoiding lock-in. Creating an interim category of provisionally recognized activities under the Paris Agreement would better advance each objective. Ideally, interim status for specific types of CDR would create incentives to experiment with projects that advance understanding of CDR's effectiveness and impacts, yet reduce the dangers of locking in technologies that may prove unsuitable. Experimental CDR projects would also promote public dialogue regarding CDR's social and environmental consequences and shed light on its political acceptability.

Interim status for CDR might take a number of forms. Within carbon trading systems, project developers or countries might be allowed to take credit for estimated carbon removed by CDR projects for limited time periods, or to count a fraction of estimated carbon removed, with further credit subject to subsequent review. Or, accounting rules could assure countries and developers that carbon removal credits will be awarded in the future upon verification of carbon removal. Alternatively, developers or countries might be required to commit to undertaking specific future mitigation projects if their CDR efforts fail to achieve projected levels of carbon removal.³¹⁴ Interim status also could be used to directly encourage research through the awarding of carbon credits for innovative CDR research programs.

Furthermore, interim status might be accommodated through the NDCs that countries submit under the Paris Agreement. The NDCs offer room for states to experiment with a variety of measures—including CDR—to achieve their commitments.³¹⁵ The international community might adopt guidelines for incorporating CDR into NDCs, while limiting the extent to which CDR projects can be used to satisfy NDCs. Also, caps could be placed on the size of CDR

313. See NAS CDR, *supra* note 7, at 90.

314. Such a requirement would be comparable to “enforceable commitments” that states may include in their Clean Air Act State Implementation Plans, which are prepared to demonstrate compliance with National Ambient Air Quality Standards. “Enforceable commitments” are pledges by a state to propose or adopt emissions control measures, means, or techniques that will achieve additional emissions reductions. A state that fails to fulfill such pledges may be subject to an enforcement action. See *BCCA Appeal Grp. v. EPA*, 355 F.3d 817, 839–40 (5th Cir. 2003); *Comm. for a Better Arvin v. EPA*, 786 F.3d 1169, 1178–79 (9th Cir. 2015).

315. Cf. Michael C. Dorf & Charles F. Sabel, *A Constitution of Democratic Experimentalism*, 98 COLUM. L. REV. 267 (1998) (discussing “democratic experimentalism,” in which subunits of society are allowed to define their own goals and decide how to achieve those goals, in exchange for providing information).

projects. Such approaches would allow for some policy experimentation while reducing the potential for adverse consequences. Demanding that CDR be supplemental to overall emissions reduction efforts would also ease concerns about overreliance on projects whose benefits and consequences are uncertain.³¹⁶

Regardless of the form adopted, interim status should incorporate independent and periodic reviews. A review panel having scientific experts among its members should be established to determine the CDR projects eligible for interim status. The panel would consider not only whether a CDR project is technically sound, but also whether it is sufficiently advanced to qualify for interim status.³¹⁷ Subsequent reviews should evaluate the efficacy of ongoing or completed projects in removing carbon, analyze difficulties encountered, and identify adverse effects. Unintended consequences are of particular concern because “policies that are intended to promote the most radical technology, environmental, economic or social changes are most likely to also have unintended consequences.”³¹⁸

Interim status itself could be experimental in nature—that is, the rules governing CDR projects should undergo periodic reevaluation and, if necessary, revision. As an initial matter, the many uncertainties surrounding CDR necessitate some fluidity within these rules.³¹⁹ As CDR research, pilot projects, demonstration projects, and small-scale implementation projects go forward, they will generate information regarding the technologies as well as the rules. Such information can enable policymakers to update and improve the legal regime governing CDR.³²⁰

However, balancing flexibility against stability will pose an important challenge. Investors and other key stakeholders will require policy stability in order to move forward with CDR development and deployment.³²¹ As the RFS experience illustrates, excessive flexibility to respond to changing circumstances

316. See CRAIK & BURNS, *supra* note 101, at 7.

317. *Cf. id.* at 7 (suggesting that NDCs be limited to “use of well-tested technologies” through “best available science” criterion in article 4(1) of Paris Agreement). Ocean iron fertilization offers an example of a proposed CDR strategy that would likely fail to meet such a threshold. A National Academy of Sciences report found “a near consensus that at climatically relevant levels of deployment potential risks outweigh potential benefits” and suggested that such “CDR approaches that raise novel risks and governance issues” be treated akin to albedo modification proposals. NAS CDR, *supra* note 7, at 92–93.

318. Marchant, *supra* note 311, at 845.

319. See generally Sofia Ranchordás, *Innovative Experimentalism in the Age of the Sharing Economy*, 19 LEWIS & CLARK L. REV. 871, 883–86 (2015) (discussing uncertainties faced by innovators and potential regulators of innovation).

320. See Jacob E. Gersen, *Temporary Legislation*, 74 U. CHI. L. REV. 247, 267 (2007); but cf. Michael Livermore, *The Perils of Experimentation*, 126 YALE L.J. 636, 642 (2017) (“Whether policy experimentation can be expected to lead to socially beneficial outcomes depends on the balance between deliberative information and political information and how that information is put to use.”).

321. See Ranchordás, *supra* note 319, at 912 (explaining that experimental regulations must be both temporary and of adequate duration); Gersen, *supra* note 320, at 277–78 (discussing concerns that actors might overrespond to a temporary regime (to derive all potential benefits before the regime ends) or underrespond (to avoid costly behavioral changes that may not be required once the regime ends)).

can “imbue[] the entire market with perpetual uncertainty.”³²² Year-to-year adjustments proved too frequent in the case of the RFS, and political pressures have virtually guaranteed the issuance of waivers each year. A similar approach to CDR would create excessive instability for technology development. To provide greater stability, CDR project developers could be given assurances that any future policy changes would have only a prospective effect—in other words, changes would not affect carbon removal credits that have been or might be awarded for previously approved projects. Alternatively, policy revisions could be scheduled in advance to occur at multi-year intervals.

None of this is to contend that CDR projects are ready to be fully integrated into existing carbon markets. Difficulties in determining actual carbon benefits argue for proceeding with caution to avoid undermining the integrity and stability of carbon markets.³²³ Allowing CDR credits to offset GHG emissions could weaken mitigation efforts.³²⁴ And while carbon markets might play an ancillary role in stimulating emerging technologies, targeted support for CDR would likely have a greater impact.³²⁵

Indeed, even a guaranteed market for CDR may not bring about activity sufficient to promote learning and innovation. As the RFS’ failure demonstrates, simply mandating the massive scale-up of an immature technology may not be enough. The liberal granting of waivers obviously undermined the RFS. Equally important, neither the technology—nor the extensive infrastructure needed to make it all work—was ready to produce biofuels on a commercial scale.³²⁶ Similarly, CDR technologies are immature and will require extensive supporting infrastructure. Commercialization will require direct financial support, whether in the form of R&D funding, subsidies, or loan guarantees.

4. Investing in Carbon Storage

Broad implementation of BECCS or DACS is unlikely unless the infrastructure for capturing and storing carbon is already in place.³²⁷ The infrastructure requirements could be immense: a National Academy of Sciences report estimates that achieving the 2C goal would “require[] a thousand-fold increase in the current sequestration activity and the construction and operation of hundreds to thousands of individual sources and injection sites.”³²⁸

Developing carbon storage capacity would support ongoing mitigation efforts while laying the groundwork for CDR approaches like BECCS and DACS. Although experts believe carbon storage capacity worldwide to be “more

322. Powers, *supra* note 185, at 148.

323. See McLaren, *supra* note 17, at 498.

324. See *id.*

325. See *id.*

326. See Powers, *supra* note 185, at 154; see also *supra* Part III.B.

327. See Vaughan & Gough, WPD 1b, *supra* note 19, at 27 (noting “path dependency of BECCS on the existence of a CCS infrastructure”).

328. NAS CDR, *supra* note 7, at 70.

than adequate,”³²⁹ developing usable carbon storage facilities is no simple matter. The process can take from one to fifteen years, as specific geologic formations must be studied individually to estimate storage costs and to determine their integrity and suitability for long-term carbon storage.³³⁰ Because industry faces little financial incentive to engage in this risky and expensive process, public sector involvement may be necessary.³³¹ Governments can develop carbon storage facilities directly, or they can encourage the private sector to do so by promising returns on capital, guaranteeing market share, or offering other incentives.³³² New models for financing carbon storage also could stimulate investment.³³³ Ultimately, the development of storage sites could lay the groundwork for private investment in CDR projects by ensuring storage availability at a known price.³³⁴

Carbon storage development faces not only physical and financial barriers, but also legal and social ones. These barriers include potential long-term liability from the escape of carbon from storage facilities as well as responsibility for storage facilities postclosure.³³⁵ Ways to address such concerns include contractual arrangements, financial mechanisms, insurance policies, or government regulations.³³⁶ In some jurisdictions, changes in the law may be necessary to allow for carbon storage, clarify property rights, address potential contamination, or resolve conflicts over subsurface use.³³⁷ Engagement with local communities and other stakeholders can not only address societal concerns at the project level, but also raise awareness of carbon storage and CDR among the general public.³³⁸

Investing in carbon transport, in addition to carbon storage, might seem like a logical step as well, since CDR and CCS both require systems to transport carbon to storage facilities. While the development of some transport infrastructure may make sense, the task is both less feasible and less pressing than developing carbon storage. To establish a carbon transport system, one must first determine where pipelines should go, which requires identification of

329. IEA 2016, *supra* note 105, at 47.

330. *See id.* at 47; Gough & Vaughan, WPD 1a, *supra* note 19, at 18; IEA 2013, *supra* note 229, at 17 (explaining that a suitable formation “must have sufficient capacity and injectivity to allow the desired quantity of CO₂ to be injected at acceptable rates” and must be able to prevent the CO₂ from reaching the atmosphere, potable groundwater, or other sensitive regions).

331. *See* IEA 2013, *supra* note 229, at 17.

332. *See* IEA 2016, *supra* note 105, at 71; IEA 2012, *supra* note 229, at 29.

333. *See, e.g.*, IEA 2016, *supra* note 105, at 97–101 (proposing disaggregated approach to storage akin to arrangements for electricity delivery under a power purchase agreement).

334. *See* IEA 2016, *supra* note 105, at 71, 100.

335. *See id.* at 98; IEA 2013, *supra* note 229, at 19; Jacobs, *supra* note 225, at 588, 590 (noting concerns regarding long-term liability and proposed model liability regimes that would provide for a government entity to take ownership of and responsibility for sequestered CO₂ after closure of storage site).

336. *See* IEA 2016, *supra* note 105, at 98–99; Jacobs, *supra* note 225, at 596–97 (suggesting need for federal liability framework for CCS).

337. *See* IEA 2013, *supra* note 229, at 17–18; Jacobs, *supra* note 225, at 594, 598–601.

338. *See* IEA 2016, *supra* note 105, at 48–49.

carbon sources and carbon storage sites. At the same time, transporting carbon, in contrast to storing it, is “the most technically mature step in CCS.”³³⁹ The construction of CO₂ pipelines may face regulatory barriers and public opposition, but as a technical matter would be relatively easy to scale up in short order.

Developing carbon storage or transport facilities does increase the risk of locking in BECCS, DACS, or any other CDR technologies that might make use of those facilities. However, these technologies are unlikely to be widely deployed in the absence of additional policies that affirmatively support them.³⁴⁰ The risk of lock-in would also be lessened by the fact that CDR technologies would have to compete with CCS for the use of these facilities.³⁴¹

5. Accounting

Reliable accounting of net carbon emissions is necessary for CDR to work and for policymakers, investors, and the public to support CDR. Most GHG accounting systems already include CCS, and a few even provide for possible recognition of negative emissions from BECCS.³⁴² These systems are hardly uniform, however.³⁴³ California—a leader in climate policy—has yet to adopt an accounting system for CCS, and its deliberations on the subject reveal some of the difficulties at hand. The California Air Resources Board studied nine existing accounting protocols for CCS and found that only four set out calculation procedures for quantifying CCS reductions.³⁴⁴ The California Air Resources Board is developing its own protocol that may incorporate elements of these four other protocols, but must first grapple with issues such as defining leakage, setting system boundaries, accounting for displaced carbon emissions, ensuring permanence, and addressing liability concerns.³⁴⁵

Developing carbon accounting protocols for CDR poses an even greater challenge because of the additional steps that must be analyzed and the uncertainties associated with those steps.³⁴⁶ For example, any CDR protocols should account for the fact that removals of CO₂ from the atmosphere will be partially offset by releases of CO₂ from natural sinks. Furthermore, questions of

339. IEA 2013, *supra* note 229, at 16.

340. See Gough & Vaughan, WPD 1a, *supra* note 19, at 31 (“[A]ny large scale expansion of CCS technology is dependent on regulatory and policy measures to incentivise and manage its deployment, such as strict emission limits or a high carbon prices alongside an adequate regulatory framework to govern both short- and long-term liabilities and responsibilities[.]”).

341. Accomplishing the 2C goal will likely require, aside from CDR, application of CCS to existing coal-fired plants, gas-fired power plants, and industrial facilities. See IEA 2016, *supra* note 105, at 15, 51–54.

342. See Kemper, *supra* note 43, at 416, 425–26.

343. See Fuss et al., *Research Priorities*, *supra* note 13, at 7.

344. See CALIFORNIA AIR RESOURCES BOARD, AIR RESOURCES BOARD’S CARBON CAPTURE AND SEQUESTRATION PROGRAM: 2016 PROGRESS AND FUTURE PLANS 6–7 (2016).

345. See *id.* at 6–7.

346. See, e.g., INTERNATIONAL ENERGY AGENCY, COMBINING BIOENERGY WITH CCS: REPORTING AND ACCOUNTING FOR NEGATIVE EMISSIONS UNDER UNFCCC AND THE KYOTO PROTOCOL 17–19 (2011) (discussing various challenges in ensuring accurate accounting for BECCS).

additionality will be posed by CDR techniques that accelerate natural processes or enhance activities that are already occurring. For example, ocean fertilization efforts should receive credit only for the additional carbon those efforts sequester, after subtracting the carbon that the oceans would have removed naturally. Similarly, accounting for BECCS should consider whether preexisting land use would have sequestered any carbon prior to conversion of land to bioenergy crop cultivation. Uncertainties surrounding such issues make it too soon to complete a carbon accounting for any CDR technique.³⁴⁷

Notwithstanding these difficulties, policymakers at international, national, and subnational levels should prioritize refining and standardizing accounting for CCS. Doing so would facilitate CCS deployment while laying the foundation for accounting systems for BECCS and DACS.³⁴⁸ Improving carbon accounting would advance the CDR policy objectives of gathering information, increasing transparency, and undertaking no-regrets measures.

6. Carbon Pricing

Finally, establishing a price on carbon would create an incentive to develop and deploy measures to combat climate change generally, including CDR. As noted earlier, it is unlikely that a carbon price alone would lead to CDR deployment so long as CDR's costs remain high. However, carbon pricing would foster a positive environment for CDR investment and development while avoiding lock-in: a carbon price allows market actors flexibility in deciding whether to pay for carbon emissions, reduce emissions, or—if legally permissible—to use CDR to remove carbon from the atmosphere. In addition, revenue from a carbon tax or from auctions of carbon allowances could be directed in part toward CDR research or toward compensating communities adversely affected by CDR projects. While the details of a carbon pricing regime are beyond the scope of this Article and have been widely discussed elsewhere,³⁴⁹ carbon pricing is a no-regrets measure that should be adopted because of its climate benefits, regardless of its ability to incentivize CDR specifically.

347. Even with more information, a definitive carbon accounting may be impossible because “[e]stablishing additionality is inherently political.” Charlotte Streck, *Ensuring New Finance and Real Emission Reduction: A Critical Review of the Additionality Concept*, 5 CARBON & CLIMATE L. REV. 158, 167 (2011) (explaining that “it is impossible to ever verify a counterfactual baseline”).

348. See CBD 84, *supra* note 6, at 57.

349. See, e.g., Shi-Ling Hsu, *A Complete Analysis of Carbon Taxation: Considering the Revenue Side*, 65 BUFF. L. REV. 857 (2017); David M. Driesen, *Putting a Price on Carbon: the Metaphor*, 44 ENVTL. L. 695 (2014); Joseph E. Aldy & Robert N. Stavins, *The Promise and Problems of Pricing Carbon: Theory and Experience*, 21 J. ENV'T & DEV. 152 (2012); ENVIRONMENTAL DEFENSE FUND, *DOUBLING DOWN ON CARBON PRICING: LAYING THE FOUNDATION FOR GREATER AMBITION 4–5* (2016), https://www.edf.org/sites/default/files/doubling_down_carbon_pricing_edf-ieta.pdf.

CONCLUSION

Incentivizing technology development is not a new challenge. In the environmental arena, governments have attempted various combinations of research grants, subsidies, intellectual property protections, regulatory mandates, and other policy instruments to promote the development of pollution control devices, renewable energy, and cleaner methods of production. Even with ambitious targets and strong government support, success is not guaranteed.

CDR poses an especially difficult challenge because of the contemplated scale of deployment, the immature state of CDR technologies, and the ambivalence with which CDR is viewed. To be effective, CDR likely would have to be deployed in numerous countries, across large land areas, and over extended time periods. In addition, CDR is not ready to be deployed on a global scale; indeed, some CDR technologies may never be technically or economically feasible. Furthermore, while CDR appears increasingly essential to achieving the Paris 2C goal, the international community has shied away from a formal commitment to CDR or even an open discussion of the subject. Under the circumstances, policy makers face a delicate task of incentivizing CDR development without prematurely committing to any specific CDR technology or to CDR technologies in general. At the same time, the increasingly urgent climate crisis demands that policy makers “make an explicit decision either to invest in the necessary research, development and demonstration of the technologies or to explain how they propose to meet their ambitious targets without such interventions.”³⁵⁰

This Article proposes a CDR policy that enables learning opportunities, mainstreams public and policy discussion of CDR, undertakes measures to advance both CDR development and other societal objectives, and avoids lock-in. Elements of CDR policy should include: supporting research and development of a wide range of CDR techniques, acknowledging explicitly the probable role of CDR in achieving the 2C goal, establishing interim status under climate regimes for CDR projects, investing in carbon storage, developing carbon accounting mechanisms, and instituting carbon pricing. These measures would greatly advance our understanding of CDR’s potential role in combating climate change under the Paris Agreement.

350. Kruger et al., *supra* note 122.

APPENDIX: TABLE OF ACRONYMS AND ABBREVIATIONS

ARPA-E	Advanced Research Projects Agency-Energy
BECCS	bioenergy with carbon capture and sequestration
CCS	carbon capture and sequestration
CDM	Clean Development Mechanism
CDR	carbon dioxide removal
CO ₂	carbon dioxide
DACS	direct air capture and storage
EPA	Environmental Protection Agency
GHG	greenhouse gas
Gt CO ₂	gigatons of carbon dioxide equivalent
IAM	integrated assessment model
NDCs	nationally determined contributions
REDD+	reducing emissions from deforestation and forest degradation
RFS	renewable fuels standard
SRM	solar radiation management