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A Precautionary Assessment of Systemic Projections and Promises From Sunlight Reflection and Carbon Removal Modeling

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Climate change is a paradigmatic example of systemic risk. Recently, proposals for large-scale interventions—carbon dioxide removal (CDR) and solar radiation management (SRM)—have started to redefine climate governance strategies. We describe how evolving modeling practices are trending toward optimized and "best-case" *projections*—portraying deployment schemes that create both technically slanted and politically sanitized profiles of risk, as well as ideal objectives for CDR and SRM as mitigation-enhancing, time-buying mechanisms for carbon transitions or vulnerable populations. As *promises*, stylized and hopeful projections may selectively reinforce industry and political activities built around the inertia of the carbon economy. Some evidence suggests this is the emerging case for certain kinds of CDR, where the prospect of future carbon capture substitutes for present mitigation. Either of these implications are systemic: explorations of climatic futures may entrench certain carbon infrastructures. We point out efforts and recommendations to forestall this trend in the implementation of the Paris Agreement, by creating more stakeholder input and strengthening political realism in modeling and other assessments, as well as through policy guardrails.

KEY WORDS: Carbon dioxide removal; modeling projections; precautionary measures; solar radiation management; systemic risk

1. CLIMATE INTERVENTIONS

Climate change is a paradigmatic example of systemic risk (IRGC, 2018; Schweizer, 2019). A problem of civilizational scope, addressable only by costly collective action, climate change is consistently under-prioritized in political platforms and public imaginations. Recently, proposals for large-scale climate interventions have started to redefine governance strategies. We inquire whether these proposals might alter or entrench the systemic risks of climate change, how we might know, and how we might forestall perverse outcomes in the near-term.

Standard practice distinguishes between schemes that mask global warming by reflecting some sunlight back into space (solar radiation management, or SRM) and sinks that remove emitted carbon from the atmosphere (carbon dioxide removal, CDR). The most visible SRM proposal is *stratospheric aerosol injection (SAI)*, a planetary scheme for a reflective particle layer maintained for decades in the upper atmosphere with adapted aircraft. CDR proposals are more heterogeneous, ranging from technological systems such as *direct air capture (DAC)* to "nature-based" proposals tied to ocean, land-use, and forest governance. One of the most discussed CDR approaches is *bioenergy carbon capture and*

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storage (BECCS), proposing that biomass energy can be combined with carbon capture and storage (CCS) to result in an overall removal of carbon dioxide from the atmosphere, or "negative emissions" (Waller et al., 2020).

For much policy-oriented work, individual approaches have different costs, processes, time horizons, and risk profiles. Yet, the grouping together of SRM and CDR in seminal reports as "climate engineering"—deliberate large-scale interventions in the climate system to counteract climate harms (e.g., Shepherd et al., 2009)—reflects some original understanding of scale and intentionality. These were proposals crafted as responses to a systemic problem, and may represent a scale of activity, some manifestation of the Anthropocene's zeitgeist, or unconventional climate strategies that merit a precautionary approach.

In this article, we explore two questions with a precautionary stance.[1] First, what are some systemic implications—means and ends, benefits and risks—of SRM and CDR? Second, what are the processes of risk assessment that identify systemic implications and judge benefits and risks? We focus on the implications of SRM and CDR as *projections* of sustained deployments, derived primarily from climate and economic modeling as resonant tools of future-oriented analysis. We supplement these with a view of SRM and CDR as resonant *promises* derived imperfectly from modeled projections, which imperfectly influence research, policy, and industry planning in the near-term. Section 2 engages with risk governance frameworks for addressing systemic risks, and discusses overlaps with future-oriented risk assessment work in SRM and CDR. Section 3 explores modeling-reliant assessments of the systemic implications, and Section 4 follows by exploring some promises posed by projections today. Section 5 concludes with measures for precautionary assessment and policy guardrails.

2. FUTURITY AND SYSTEMIC RISK ASSESSMENT

Risk governance rationales underpin much of the research on and assessment of SRM and CDR, via scenarios developed by a range of modeling and qualitative methods.

We highlight overlaps between SRM and CDR assessment and a systemic risk governance framework, and draw three insights.

The International Risk Governance Council (IRGC) has updated its assessment and governance frameworks to account for *emerging risk* (IRGC, 2015) and *systemic risk* (IRGC, 2018). Emerging risks embody novel problems, and can be entirely new fields of risk, or existing debates reshaped by novel conditions. The emerging risk governance framework emphasizes scoping and precaution (Grieger, Felgenhauer, Renn, Wiener, & Borsuk, 2019; IRGC, 2015). Systemic risks have metastasized into wicked problems with unclear lines of causation, ripple effects, and reach across borders and governance areas—the governance focus, relatively, is on coping and resilience (IRGC, 2018; Schweizer, 2019). The assessment and governance of either can be conditioned by *complexity*—an unclear and evolving ecosystem of causes and effects; *uncertainty*—limitations in scientific knowledge; and *ambiguity*—the presence of conflicting beliefs and values (IRGC, 2018).

We see CDR and SRM as issues of emerging risk that could lessen, worsen, or redistribute the systemic risks of climate change (IRGC, 2015, 2018). Emerging risks can become systemic—the movement of scientific debates to global strategies and large-scale infrastructures could have far-reaching consequences. Moreover, emerging issues can merge with and alter existing systemic issues. SRM and CDR signal possibilities for reevaluating global targets and governance strategies, and even the ideas and projections contained in research need to be gauged for game-changing potentials. At the same time, there are nuances between systemic and emerging risk governance. Emerging risk governance has a stronger explorative focus, but systemic risk assumes effects already in play, and demands urgent, fact-finding assessment and a resilience-based governance approach. We take from this our first insight: by generating space for the discussion of novel and even controversial strategies, and by doing so within the fraught politics of climate governance, SRM and CDR assessments may already be politically active. This requires immediate action.

Much of SRM and CDR assessment explores potentials and challenges at regional to global scales, often from a "benevolent planner" perspective, and with varying emphases on climatic or societal dimensions (Shepherd et al., 2009; Preston, 2013).

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[1] We do not intend to invoke the "precautionary principle," as diversely understood within international customary law (Sandin, 1999). Rather, we refer more loosely to precaution as avoiding the instrumentalization of speculative climate strategies, by introducing process-oriented measures in assessments and guardrails for policy.

Our focus lies on models underpinning the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports—the first port-of-call for mapping combinations of technologies, alternative pathways of deployment, and climatic impacts. Earth system models (ESMs) assess the physical impacts of climate change; these have been repurposed to simulate the effects of SRM and CDR schemes (Irvine, Kravitz, Lawrence, & Muri, 2016; Keller et al., 2018). Integrated assessment models (IAMs) map mitigation options, and the Paris Agreement's temperature limitation targets mostly cannot be projected without CDR (IPCC, 2014; 2018). Assessments grounded in quantitative modeling work focus on technical dimensions, and provide a "cartography" of options—from the highly idealized to the somewhat plausible—to anchor political options and societal concerns (Edenhofer & Minx, 2014). We see modeling as integral to the science-policy interfaces of the global climate regime (Edwards, 2010), as well as representative of a template of risk assessment based on modeling, engineering, and pilot projects to incrementally gauge the implications of rollout (Keith & Irvine, 2016; Minx et al., 2018).

Qualitative assessment grounded in the social sciences deploys further mixed methods, ranging from thought experiments and analogies, to surveying and horizon-scanning, engagement forums, and foresight scenarios common in industry and governmental planning (Low & Schäfer, 2019). Qualitative work can share with modeling the creation of experimental futures for informing policy. However, as part of "responsible research and innovation" frameworks, they have also been more commonly intended to generate open-ended discussion of concerns from different perspectives (Low & Buck, 2020). The focus has been on process rather than output; the social construction of risk more so than actionable projections of risk (Stilgoe, 2015). From this range of futuring objectives and activities, we draw two insights for assessing the systemic implications of CDR and SRM. First, much assessment in this space is already at the systemic level, but different kinds of assessment—for example, modeling and stakeholder-facing engagements—emphasize different kinds of knowledge and risk (Low & Buck, 2020, Forster, Vaughan, Gough, Lorenzoni, & Chilvers, 2020; Waller et al., 2020). Second, projections of the future afford us an opportunity to examine how such projections are constructed by different assessment practices and communities, and how these complexes of actors and activities shape the scientific basis on which climate strategy may come to be based.

3. MODELING PROJECTIONS

We focus on CDR and SRM modeling projections as resonant steering mechanisms in both scientific work and political discourse. This section can be seen as a snapshot of the evolving modeling landscape, as well as building on previous critical assessments. We argue that a technical kind of expert knowledge is at the forefront of quantitative assessment, which shapes instrumental deployment objectives and schemes as well as incomplete profiles of systemic risk. Moreover, these projections have signals and implications for governance and policy that lie beyond the scope of technical knowledge. We emphasize nuances and overlaps between CDR and SRM modeling, and conclude with possible improvements.

3.1. CDR: Systemic Projections and Deployment Schemes

IAMs, are the primary vehicle for mapping alternative global mitigation portfolios for inclusion in IPCC reports (Cointe, Cassen, & Nadaï, 2020). The majority of scenarios underpinning the Paris Agreement targets of 2°C (IPCC, 2014) and 1.5°C (IPCC, 2018) require large-scale rollout of BECCS. Almost all scenarios reaching 1.5°C of warming and many reaching 2°C rely on BECCS to permit "overshoot"—the global economy can temporarily emit carbon in excess of a desired maximum carbon budget, followed by a period in which aggressive emissions cuts combine with BECCS to result in net-negative global emissions. Hence, it is currently the only novel carbon sink subject to concerted, systemic-level assessment (Fuss et al., 2018; Minx et al., 2018).

The scale of deployment and CDR deliverable by BECCS is likely exaggerated. IAMs can only conditionally portray constraints BECCS might face in the real world on biomass- and CO_2-storage site availability, or varying political support. Moreover, in many scenarios BECCS is the only novel CDR approach (the others are forestry management practices) represented. Nevertheless, global-scale biomass cultivation would create heavy additional demands on land use, with more immediate implications for food shortages among the most vulnerable, fragile dependence of smallholder farmers, and water and biodiversity issues (Boysen et al., 2017; Buck, 2016; Creutzig, Corbera, Bolwig, & Hunsberger, 2013; Heck, Gerten, Lucht, & Popp, 2018). These risks have to be compared against the prospects for long-term, incremental carbon removal. Assessments dispute whether limiting BECCS to current bioenergy production levels, or using marginal land and residues (rather than food crops) can significantly forestall these risks (Vaughan et al., 2018). Indeed, since the 2005 global food crisis, next-generation biofuels based on residues have yet to replace food crop fuels (Kuchler, 2014). Projections also imply a commitment toward thousands of processing plants and carbon storage sites (Nemet et al., 2018), where the threat of leakage and pollution remain popular concerns.

Less systemic-level assessment exists for other CDR approaches. *DAC* has long been an attractive possibility due to its comparatively low surface-space and environmental footprint. It is presently tied not only to possibilities for long-term CDR, but for prolonging existing oil fields (through enhanced oil recovery) and for use of carbon dioxide as a feedstock for various industrial applications. At the same time, development remains held back by high-energy requirements, as well as storage capacity, cost, and location concerns (Beuttler, Wurzbacher, & Charles, 2019). An up-and-coming suite of *marine CDR* is only now undergoing preliminary technical assessment (GESAMP, 2019). One approach, ocean alkalinization, has an additional potential of directly counteracting ocean acidification. But most ocean-based approaches are presently thought to face tremendous regulatory and logistical issues at deployment scale, and uncertainties persist over capacities and longevity of carbon storage, as well as how deployments might alter ocean properties (acidification, oxygen, nutrients) and fisheries (GESAMP, 2019).

Systemic projections of CDR come from different kinds of models and expert communities, and each gives different and incomplete depictions of risk. The role of IAMs in risk assessment is indirect but powerful: they construct technological bases and deployment objectives and schemes for BECCS. However, IAMs are economic models for "optimization," calculating the most cost-effective measures toward particular climate targets on technical and economic metrics of feasibility. IAM projections of BECCS at scale are therefore not risk evaluations of BECCS at scale—they are technically slanted, optimized, cost-effective, and apolitical portrayals.

Assessments of BECCS' feasibility and desirability have begun to question the portrayal of BECCS in IAM projections. Some inquire after barriers to large-scale rollout (Smith et al., 2016; Stavrakas, Spyridaki & Flamos, 2018; Fridahl & Lehtveer, 2018). Others explore optimistic and intransparent choices on BECCS' technical assumptions (e.g., Butnar et al., 2019; Rickels, Merk, Reith, Keller, & Oschlies, 2019). Overshoot, for example, is possible because IAMs project BECCS to have relatively low costs and large capture and storage potentials, and the scale of BECCS in projections is exacerbated where low discount rates cause deferral of costly action into the future (Asayama & Hulme, 2019). Much critique focuses on a point well known to modelers but less clearly translated to audiences: IAMs' mitigation portfolios have limited political realism and can be highly speculative, depending on what modelers and participating experts know and emphasize in technical specification and policy support (e.g., see parallels of nuclear energy in IAMs in the 1980s, or CCS and CDR more recently, in McLaren & Markusson, 2020).

BECCS has renewed debate among IAM practitioners on how to make scenarios more transparent and usable (Schneider, 1997; Gambhir et al., 2019). IAM networks take increasing precautions to clarify their work as conditional and explorative, rather than prescriptive (Rogelj et al., 2018). Assessments hedge on BECCS, pointing out the need for even more drastic, immediate, and sustained emissions reductions if large-scale BECCS is to be tempered, and noting that a varied CDR portfolio is preferable to BECCS alone (Rogelj et al., 2018). Modeling and critical commentary show signs of mutual learning, calling for extending societal and political "reality checks" in modeling to improve feasibility calculations (Forster et al., 2020; Rickels et al., 2019; Van Vuuren, Hof, van Sluisveld, & Riahi, 2017; Waller et al., 2020), as well as for bridging modeling practice, scenario users, and critics (Low & Schäfer, 2020; Edenhofer & Kowarsch, 2015). Most of all, IAM practitioners note that scenarios for detailed inclusion in the upcoming Sixth Assessment Report have gone beyond techno-economic portrayals of realism to incorporate stylized socioeconomic and policy contexts—reflecting cooperation or conflict in climate governance—as influences upon how new systems like BECCS might unfold (Rogelj et al., 2018; Riahi et al., 2017).

Yet, effects for future climate policy have already emerged. CDR's current visibility is due to BECCS' profile in IAM projections, and IAMs prioritized BECCS precisely because—as an immature technology—its components (biomass availability, storage capacity) were understood sufficiently to be calculable, but malleable enough to allow models to envision deployment at politically daunting scales. In turn, technical projections have had political effects in making the Paris targets appear achievable with (temporary) overshoot of carbon emissions trajectories, and thereby normalizing the need for CDR in climate policy (Geden, 2016, Haikola, Hansson, & Anshelm, 2019). To be clear, keeping ambitious climate targets in reach *without* large rates of carbon removal points to dramatic emissions reductions and supporting policies whose feasibilities and social implications are poorly understood (Michaelowa, Allen, & Sha, 2018; Van Vuuren et al., 2018). But it is important to remember that climate strategy is emerging—with a powerful message of allowing the carbon economy to overshoot—based on an immature carbon sink used as a modeling backstop (Beck & Mahony, 2018).

We also consider a different suite of models in the CDR space: earth systems models (ESMs) that underpin IPCC work on the physical science of climatic risk.[2] The nascent CDR Model Intercomparison Project (CDR-MIP) will gauge storage potentials and climate responses of DAC (technological CDR), afforestation and reforestation (terrestrial CDR), and ocean alkalization (marine CDR) (Keller et al., 2018).

There are not yet any published works from this project, but we can do some limited prospection on how ESMs construct risk. ESMs rely on experimental schemes and scales of CDR deployment, but in order to gauge climatic processes, feedbacks, and impacts. As a first cut of physical risk, this is important work. At the same time, ESMs constrain portrayals of political reality in two ways. Unlike IAMs, ESMs assume complete technical feasibility, whether of plausible or highly speculative approaches. Like IAMs, they assume a global planning perspective, facilitative policies, and stable political conditions that precede and sustain deployment (in scenarios included in AR5), and have limited ability to gauge perverse effects than deploying kinds of CDR might have on climate strategies.

Another consideration is that CDR-MIP straddles scientific and policy objectives. This could confuse how assessments of hypothetical schemes are communicated and applied in the future. For now, CDR-MIP has the science-facing objectives of model intercomparisons: to explore how different models calculate earth systems responses by focusing them on common deployment schemes. Many scenarios depict extreme application of CDR with substantial overshoot-and-return to study earth systems responses, rather than represent "plausible" deployment strategies (table 1 in Keller et al., 2018). How is this to be accessibly communicated in first assessments of CDR's climate risk? Moreover, CDR-MIP is in its first phase; there is an understanding of policy relevance for later phases and a limited number of experiments are tied to IPCC emissions pathways (Keller et al., 2018). How might these modeling experiments in the future be designed and communicated as deployment schemes thought to be more plausible for policy deliberation? We draw these insights because CDR-MIP uses templates and plans collaborations with a larger body of ESM work on climate risk—this time, in SRM (Keller et al., 2018).

3.2. SRM: Systemic Projections and Deployment Schemes

SRM modeling revolves almost completely around the gauging of climatic impacts through ESMs, and these set influential bounds on deployment objectives and schemes. SRM assessment is dominated by one approach—SAI—often sidelining regional schemes proposing cloud modification or the brightening of land and ocean surfaces. SAI is the only current proposal modeled on a planetary scale, is calculated to have low implementation costs, and would lower global average temperatures within weeks. For these reasons, early discussion saw SAI as a swiftly deployable response to climate emergencies, which has since been warned against (e.g., Markusson, Ginn, Ghaleigh, & Scott, 2014). SAI modeling networks largely frame SAI as a possible means to significantly alleviate climate damages, offering more time for people and ecosystems to adapt and low-carbon transitions to catch up, rather than as a substitution for emissions reductions or an emergency mechanism. A few portray SAI as a means to reduce harms for the most vulnerable (Horton & Keith, 2016).

Significant risks surround reflective materials (generally, sulfates), some of which could acidify

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[2] IAMs are quieter on options that do not fit economic modeling imperatives. Direct air capture was not cost-effective enough to be included at scale, and IAMs are not geared for ocean-based approaches.

natural systems (Kravitz, Robock, Oman, Stenchikov, & Marquardt, 2009), increase air pollution and health impacts (Eastham, Weisenstein, Keith & Barrett, 2018), and deplete the ozone layer (Nowack, Abraham, Braesicke, & Pyle, 2016). These are balanced against more visible simulations on SAI's potential to reduce the systemic risks of climate change: global average temperatures, the intensity of the hydrological cycle, certain biodiversity and agriculture losses, the strength and frequency of heavy precipitation events, and the rates of sea ice melt and sea level rise (Irvine et al., 2016). The nuances of these effects are highly dependent on two factors: the amount of warming that SAI deployment compensates for (represented by emissions pathways and atmospheric carbon), and the deployment scheme by which SAI compensates for warming. Under conditions of high emissions and warming, SAI—applied to fully counteract warming—comparatively reduces precipitation in monsoon regions (Ferraro, Charlton-Perez, & Highwood, 2014; Robock, Oman, & Stenchikov, 2008). A truly systemic concern is "termination shock": without strong and sustained emission cuts, an abrupt halt to sustained SAI deployment would result in a temperature spike to which adaptation would be difficult.

Recent modeling has attempted to reduce these projected risks (uneven effects and termination shock) by designing SAI around robust mitigation efforts. Deployment schemes are emerging as "portfolio" approaches that tie SAI schemes to CDR and mitigation embodied in IAM pathways. One type—peak-shaving—maintains a particular global temperature. Hypothetically, peak-shaving could indefinitely offset a reckless amount of warming, feeding concerns of termination shock. Scenarios have therefore tied this scheme to robust emissions reductions and CDR to reduce the size of the peak shaved (e.g., MacMartin, Ricke, & Keith, 2018). A second type aims at "imperfect limitation" of climate change. SAI would slow rather than entirely halt warming, and allow for a gradual phase-out of SAI if mitigation and CDR are correspondingly strong (Keith & MacMartin, 2015). Under these conditions, temperature and precipitation are more evenly moderated across regions, and termination shock is counteracted (Irvine & Keith, 2020; MacMartin, Caldeira, & Keith, 2014).

Three trends are emerging in SAI modeling: a pronounced policy turn, increased integration with benchmarks set by IAM emissions pathways, and optimized deployment schemes argued to be more plausible and relevant for policy. The earliest framework for SAI modeling was the Geoengineering Model Inter-comparison Project (GeoMIP), built on the objectives that inform the first phase of CDR-MIP: to induce heavy signals in the climate system for calibrating models to assess an unfamiliar kind of climate intervention (e.g., compensating for a worst-case >5°C increase, Kravitz et al., 2013). It was from many early scenarios that resonant depictions of monsoon precipitation reduction and uneven regional impacts arose. But blunt scenarios, it was argued, produce blunt impacts. An influential plurality has pivoted from understanding (how models calculate) the climatic implications of idealized deployments, to a "mission-oriented" mode of simulating and reducing uncertainties of deployments deemed plausible or representative (Keith & Irvine 2016; MacMartin & Kravitz, 2019). This has been influenced by thinking of SAI as an "optimization" issue: rather than modeling the effects of a given scheme, the modeler designs the best possible scheme to achieve a set of climate objectives (Ban-Weiss & Caldeira, 2010). There are early indications of SAI being a part of studies using IAMs (Belaia, unpublished). We should be wary of how an option perceived as "cheap, fast, and imperfect" (Mahajan, Tingley & Wagner, 2019) might be incorporated into economic models mapping mitigation options based on cost effectiveness.

Recent modeling has aimed to deliver optimized scenarios where SAI might be applied to partially counteract warming, combined with significant carbon dioxide emissions reductions—and increasingly, CDR—to reduce a range of climate harms. Designers of these emerging scenarios intend for them to add to a growing basis for policy deliberation (Keith & Irvine, 2016; MacMartin & Kravitz, 2019; MacMartin et al., 2018). These studies are described as more relevant for choices faced by decisionmakers, since they offset warming based on robust emissions reductions rather than worst-case warming (>5°C), and attempt to integrate rather than substitute for mitigation (Keith & Irvine, 2016). This is a sensible range to address. But we must be wary that labeling these deployment schemes plausible or more relevant does not inadvertently conceal the fact that these schemes are not designed to be politically, or even technically, realistic.

SAI modeling explicitly assumes cooperation (or lack of conflict) over global deployment, technical feasibility, complete control over deployment, and acknowledges but does not investigate in-depth the possibility of SAI creating perverse incentives to lessen mitigation efforts (Keith & Irvine, 2016; see also Corry, 2017; Flegal, 2018; McLaren, 2018; Wiertz, 2015; Talberg, Thomas, Christoff & Karoly, 2018). If decisionmakers treat optimized scenarios as a guide for policy deliberations, then they will insufficiently consider nonideal deployment scenarios, such as unilateral (Rabitz, 2016), competing and countering (Parker, Horton, & Keith, 2018), or decentralized schemes (Reynolds & Wagner, 2019). SAI modeling is currently much better at highlighting a global picture of allayed or redistributed climate risks, than at capturing the effects of messy, antagonistic deployments and responses. We acknowledge that ESMs are not designed to assess a more complex geopolitical calculus; our point, rather, is that a predominant focus on optimized scenarios produced by ESMs shades those considerations from view.

There is a further, unintended irony. SAI's relevance as a climate strategy is driven by assessments that it is more technically feasible than the mitigation needed for ambitious climate targets (Corry, 2017). At the same time, recent schemes that place SAI in its most ideal use and light (e.g., Keith & Irvine, 2016; MacMartin et al., 2018) are built around precisely those aggressive emissions reductions that remain unmatched by global pledges, as well as further up-scaling of CDR. More uneven regional implications, furthermore, appear in SAI scenarios that offset warming under conditions of poor mitigation, or under emergency conditions where the collapse of natural systems unexpectedly results in accelerated warming. Indeed, worse-case scenarios—with high greenhouse gas (GHG) pathways, or with less hopeful assumptions about global cooperation and controllability—might be less desirable from modeling expert perspectives (and ours), but they are plausible when considering the inertia of the carbon economy and the currently fragmented nature of global affairs. McKinnon (2019), in this vein, argues for worse-case scenarios to underpin planning for SAI governance. Even where SAI might partially counteract dramatic warming and reduce overall harms (especially in comparison to the high-GHG counterfactual), highlighting uneven, adverse outcomes is important for policy considerations.

Predominant reliance on "best-case" SAI schemes would be misleading for risk planning. We must be wary that trending modeling toward best cases of highly sanitized technical projections does not side-step concerns over political feasibility or perverse intentions—especially if they grow in demand for decision-making support. That is, after all, the unfolding story of BECCS in IAMs.

3.3. Guardrails for Modeling Risk Assessment

In this section, we look at the implications of using modeling projections for assessing CDR and SRM risk at the systemic level, and offer "guardrails" pointing out directions for clarifying how projections are created and applied. Projections are useful in offering stylized, optimized schemes as alternatives or even tentative instruction manuals. But these schemes are deceptive: they appear attractive or feasible precisely by abstracting from technical failures, messy politics, and perverse agendas. In this manner, modeling projections offer only partial depictions of systemic risk (as defined by IRGC, 2018 or Schweizer, 2019). The scope is global and seeks to include additional dynamics such as climatic feedbacks (*scope* and *complexity*). Otherwise, limitations in knowledge, or *uncertainty*—and a limiting of relevant knowledge to the technical rather than diverse knowledge types, see *ambiguity* (IRGC, 2018)—are often overshadowed in a rush to develop options for buying time to achieve ambitious climate targets. This mode of assessment trends towards "solutionism." Complex dimensions are described in technical or economic terms for better digestion in policymaking, choices between kinds of politics are substituted for choices between kinds of technology (Lövbrand et al., 2015), and planning for those technologies is driven toward consensus on long-term controllability and near-term necessity (Asayama, Sugiyama, Ishii, & Kosugi, 2019; Corry, 2017; Voß, Smith, & Grin, 2009).

Quantitative modeling is therefore indispensable, but the portrayal of modeling as explorative, technically focused mappings for supporting decision making is simplistic. Expert choices on modeling parameters and scenario design reflect political judgments; political and societal implications are contained in technical scenarios (Ellenbeck & Lilliestam, 2019; McLaren, 2018).[3] Technical assessments do not adequately consider that cleanly optimized projections of potentially controversial options not only inform but direct deliberations on climate strategy (Beck & Mahony, 2018 on BECCS in IAMs). This shaping potential is intensified by two trends:

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[3] This is endemic to the projection of all mitigation efforts, from power sources, to industrial production, to consumption patterns.

Modeling work increasingly structures itself for relevance in policy, while trending toward targets and parameters described as plausible. Early phases of GeoMIP and CDR-MIP may be science-facing, but IAM work for IPCC reports is—and an increasing amount of SAI modeling aspires to—what Gieryn (1983) calls "mandated science," or the explicit production of assessment as decision-making support.

Moreover, there have been calls for emphasizing more realistic IAM scenarios as a guide for investors and policymakers based on "the gulf between where the world is heading (between 3°C and 4°C) and where it has agreed to go (1.5–2°C)', with a focus on likelihood rather than range of climatic outcomes (Hausfather & Peters, 2020). In IAM pathways, movement toward usability of realistic projections is intended to encourage investments and policies for systems with better-known specifications (Hausfather & Peters, 2020). We should be wary that declaring the viability or desirability of ambitious emissions pathways or temperature targets does not shade over the differences in feasibility and risk between the various energy and technological systems that comprise them, and thereby instrumentalize SRM and CDR.

We must be careful not to blame models for what they are not designed to do, as much as connect modeling practice to a wider array of assessment objectives and approaches. Modeling work already takes the initiative. The IAM community is increasing focus on fine-tuning model inputs through "reality checks" with technology experts and social scientists, and improving feedback between modelers and users on how to extend the range of technologies, climate targets, and scenarios assessed (Gambhir et al., 2019; Edenhofer & Kowarsch, 2015). A funding program has helped create a number of SAI modeling projects in which research groups in the global South model the effects of SAI schemes for their regions (for the first publication, see Pinto, Jack, Lennard, Tilmes, & Odoulami, 2020).

These have been supplemented by activities using models as a platform for participation and deliberation—integrating diverse knowledge types and users in designing modeling projects (Low & Schäfer, 2020; Salter, Robinson, & Wiek, 2010); or evaluating how modeling and politics influence each other at important interfaces (e.g., between IAMs, IPCC assessments, and UNFCCC agendas—see Beck & Mahony, 2018). Idealized deployment schemes can in particular be connected to works on perverse agendas and nonideal conditions for development and deployment (McKinnon, 2019; Parker et al., 2018; Rabitz, 2016; Reynolds & Wagner, 2019). Foresight and engagement work designed around soliciting stakeholder concerns can help generate overlooked rationales for and against SRM and CDR, as well as plausible political contingencies and feedbacks (Talberg et al., 2018; FCEA, 2020; Low, 2017).

Researchers can better maintain an accessible overview of the range of CDR and SRM schemes and outcomes. Summarizing reports (which nonmodelers turn to for first contact) tend to describe the implications of SRM and CDR in aggregate, without sufficient nuance toward the deployment parameters highlighted by individual studies as hugely influential for the depiction of risk—for example restrictive and facilitative technical and socioeconomic conditions, or matching against high and low emissions pathways and atmospheric concentrations. Even in broad strokes, what are preconditions that underpin different deployment schemes and scenarios? What tentative level of confidence is there for a given risk profile; do these risks represent well-understood and immediate problems or long-tail contingencies, and why (Parson, 2008)? At the level of research communities: given increasing signs of coordination, what can early CDR work in earth systems modeling learn from SRM work? If SRM is to be included in IAM modeling, how can its low costs prevent it from becoming a new stopgap toward the Paris targets? There is room for optimal schemes to be highlighted. Yet, an accessible overview might avoid prematurely narrowing options to a small number of standardized necessities that remain highly speculative.

4. NEAR-TERM PROMISES

If Section 3 was an analysis of the explorative aspects of quantitative modeling, this section examines modeling as immediately and politically active. Modeling can create alternative projections of systemic and long-term deployments. But any risk assessment must also gauge the near-term impacts of projections themselves in shaping climate governance. Moving from modeling to pilots to rollout tacitly correlates impact with stages in up-scaling. Technical risk therefore increases explicitly with scale; societal risk implicitly so.

We treat projections of SRM and CDR as *promissory*—they are meaningful in the present for what they promise for climate governance in the future (Beck & Mahony, 2018 for BECCS, Flegal, 2018 for SRM). We take this concept of "promises" from studies of how visions of an immature technology's future usage can imperfectly influence the development and governance of that technology at its earliest stages (e.g., Brown, Rappert & Webster, 2000—one can also think of "promises" as "expectations" or "signals"). But this potential can trend in different directions. Modeling can explore bounds on how SRM and CDR are to be ideally integrated into mitigation and adaptation, and signal what actions are needed to incentivize them or navigate challenges they pose. At the same time, projections designed by scientific networks graft onto pre-existing agendas in policy and industry, and the combination of these intents has profound implications.

There is much commentary on the systemic implications of even thinking about SRM and CDR. A nonexhaustive list of concerns includes de-incentivizing more comprehensive but costly mitigation efforts; scrambling established agendas regarding mitigation and adaptation for research, policy, industry, and international negotiations in climate governance; using the promise of buying time to pass responsibilities for mitigation to future generations or to entrench existing agendas; altering relationships with nature from a conservationist to a managerial ethic; and creating path dependencies toward deployment (Hale, 2012; Preston, 2013; Shepherd et al., 2009). Others note that concerns have not clearly manifested and do not disqualify the need for research (Reynolds, 2014), and that failing to develop CDR might reduce future capacities for mitigation (Honegger & Reiner, 2018).

We will not retrace these possibilities in detail. Rather, we question if these are emerging in policy and industry platforms, and connect them to the content and signals of modeling projections. CDR is only beginning to emerge into mainstream agendas, and SRM may not be at all. However, we tentatively observe that key framings of time-buying strategies from modeling projections are grafting onto the politics of delaying decarbonization. Meanwhile, discussions of how to integrate SRM and CDR with robust emissions reductions have yet to emerge.

4.1. CDR: Promises and Near-Term Effects

Assessments could spur investments and incentives in cautious, incremental ways (Haszeldine, Flude, Johnson, & Scott, 2018), allowing CDR to ease transitions to a low carbon economy and offset residual emissions left from sectors that are harder to transform (Geden, Peters, & Scott, 2019; Luderer et al., 2018). At the same time, a central promise of carbon removal as projected by IAMs is the capacity for the global economy to overshoot near-term carbon budgets. The danger here is that CDR will not supplement deep-lying decarbonization as much as delay it by presenting a promise of paying back "carbon debt" in the future, and by meanwhile entrenching carbon infrastructures (Asayama & Hulme, 2019; McLaren, Tyfield, Willis, Szerszynski & Markusson, 2009).

Already, there are political effects. The promise of overshoot has been able to maintain perceptions that the Paris targets of 2°C and 1.5°C remain achievable,[4] and this is allowing a stylized understanding of CDR as the expansion of carbon sinks to become entrenched (Beck & Mahony 2018; Geden, 2016; Haikola et al., 2019). BECCS is being increasingly questioned in scientific assessment, but the necessity of carbon removal writ large is implicitly tied into political platforms. The Paris Agreement describes a "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases" by the second half of the century, and CDR is permissible in National Determined Contributions (NDCs) (Craik & Burns, 2019). A growing number of countries and cities have pledged to reach carbon neutrality by 2050 or earlier, following from UNFCCC deliberations. These are not clear statements of intent regarding CDR deployment. Rather, it is more likely that the idea of CDR has become normalized, and governments are only beginning to deliberate on the implications for their climate commitments. We must be wary however, that if novel CDR is included in NDCs—as with forestry management practices, which are sometimes described as terrestrial-CDR—than these do not delay efforts toward conventional emissions reductions. There are already indications that this could be the case for large-scale afforestation pledges (Holl & Brancalion, 2020).

McLaren et al. (2019) summarize ways in which the development of BECCS at the project level may have replaced rather than reinforced conventional emissions reductions. Primarily, this has been via "fungible accounting" that blurs distinctions

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[4] Recent IAM work, in response to criticisms over BECCS' large profile, has mapped scenarios in which aggressive and immediate mitigation can achieve the 1.5°C target without overshoot and only limited CDR (Rogelj et al., 2018). Yet, it is clear that these scenarios rely on heroic assumptions regarding other mitigation activities.

between negative emissions and emissions reductions. Moreover, in emerging industry practice, BECCS development does not follow the template laid out by IAMs: a more carbon-heavy mode of biomass energy is used, ensuring that much less carbon is captured, and this is diverted to enhanced oil recovery (a method for prolonging the use of existing oil fields) rather than to storage areas (McLaren et al., 2019). Other variants of CDR may be following in these tracks—DAC) and carbon utilization are also discussed as part of enhanced oil recovery, or carbon offsetting as part of emission trading schemes (McLaren et al., 2019, see also Honegger & Reiner, 2018).

There are further cautionary lessons from previous climate strategies. "Overshoot" ties to a rationale with some traction in historic climate governance: bridging or time-buying strategies that might soften the near-term impacts for transitioning industries and infrastructures entrenched in the carbon economy. The closest parallel is CCS, which shares needs in infrastructure and incentivization with BECCS and DAC. The rationale of CCS was to decarbonize high-emissions industries in the near-term and prolong fossil-fuel reliant power production, thus promising to decouple (to a degree) emissions from the carbon economy (Bäckstrand, Meadowcroft, & Oppenheimer, 2011). But—and this is key to systemic risk—CCS has never been implemented at scale despite being highly visible in IAM pathways, the subject of industry hype for over a decade, and new plants labeling themselves as "CCS-ready" (Krüger, 2017; Markusson, McLaren, & Tyfield, 2018). Today, CCS is contained in a handful of projects for enhanced oil recovery—to which some CDR technologies are being linked. Certainly, strong civic opposition (Lipponen et al., 2017) and insufficient policy support (Haszeldine et al., 2018) played a role. But we should also consider that the observable impact of CCS is as a promise rather than a reality—the promise creates expectations that carbon infrastructures have time to transition, while the reality leaves those infrastructures in place. CDR may fulfill the same uses. Royal Dutch Shell has built scenarios around the expectation of CDR and the capacity of overshoot to maintain their own production in the face of a 2°C target; although as with other actors, we should see this as planning rather than intent (Carton, 2019).

Analysts often focus on the large-scale risks of rapidly expanding CDR across a variety of natural systems and sectors. But as CDR is normalized in policy, we do not sufficiently consider the possibility for the promise of CDR to feed into practices built around the near-term stability of the carbon economy (McLaren & Markusson, 2020).

4.2. SRM: Promises and Near-Term Effects

SRM and CDR pose radically different technical characteristics and risk profiles in modeling projections, but their usages as climate strategies are comparable. An important promise of SRM is also to buy time for mitigation efforts to scale up (Buck et al., 2020), and, given its swift-acting potential, to reduce harms for vulnerable demographics and ecosystems (Horton & Keith, 2016). Concerns remain, however, about the effects that considering SRM might have in lessening mitigation efforts. These follow a similar logic to those of CDR and antecedent climate strategies such as CCS—the promise of a "temporary" overshoot of carbon or temperature trajectories becomes inertial, with SRM acting as the "cheap and fast" safety net that might never materialize (Asayama & Hulme, 2019; McLaren, 2016). Corry (2017) additionally points out that the measured multilateral schemes assumed by modeling are divorced from international politics, and that SRM could strengthen national security logics in climate governance without ever being deployed.

We cannot say that SRM has observable implications for locking-in carbon structures, substituting for emissions reduction, or introducing brinksmanship. SRM has not emerged onto mainstream industry platforms. This is partially because SAI is thought of in centralized and global schemes, rather than—like CDR—distributed approaches operationalized at local to regional levels. Bottom-up incentivization through markets or the private sector is rarely thought of as necessary or desirable, although some map intellectual property concerns and envision safeguards for maintaining the public nature of SRM development (Reynolds et al., 2017). At the same time, the key concern is not the direct participation of industries in SRM development, but their planning of future operations around the prospect of its deployment—as we may already be seeing with CDR.

SRM is more conventionally thought to be a matter for states, but beyond scoping reports sponsored by national research bodies or government ministries, there is no clear government sponsorship. Moreover, SRM's path of entry into international climate governance is indistinct. The language of the

Paris Agreement provides no clear room for SRM, as it does not directly reduce emissions or enhance sinks (Craik & Burns, 2019). However, the strengthened focus on temperature targets (2°C or 1.5°C) in the Agreement's objectives (Article 2.1a) may be more facilitative of SRM than previous target metrics that focused on greenhouse gas reductions (Horton, Keith, & Honegger, 2016; McLaren & Markusson, 2020). Otherwise, the legal analysis of Craik and Burns (2019) shows that it is difficult to speculate about where SRM would fit (the NDCs, Article 4; as adaptation, Article 7 and 8). At the least, there is the sensitive issue of reordering the terms of "Common But Differentiated Responsibilities and Respective Capabilities" under which North-South inequities regarding mitigation have been navigated (Flegal & Gupta, 2018). If SRM is considered at the state level, the first conversations may occur minilaterally. It is, perhaps, a space to watch.

4.3. Guardrails for Near-Term Effects

It is perhaps the promises of modeling projections that have the most potential for systemic impacts in the near-term. We posit that projections and promises from modeling scenarios are imperfectly coupled. The promise of CDR and SRM—that they might buy time for the carbon economy—may be far more resonant for entrenched industrial and political interests than the details of "best case" modeling deployments highlighting the need for robust accompanying efforts at mitigation. We must be wary that technical, optimized, cost-effective, apolitical modeling does not graft selectively onto the politics of delay. Here, it is not sufficient for scientists to improve modeling processes (Section 4.3), or communicate that SRM and CDR cannot substitute for mitigation. We need guardrails tailored to industry and policy.

Increasing attention is paid to how to incentivize CDR. For some, the technical diversity and geographic distribution of kinds of CDR requires decision making at the most localized level possible. Publics should be involved from the project level up in gauging concerns, and informing the development of incentivizing and risk management policies (Bellamy, 2018). Others focus on the coordinating, catalyzing, and regulatory roles playable by regional (the European Union, Geden et al., 2019) and international governance (the Paris Agreement, Honegger & Reiner, 2018). These might include incentivizing—with BECCS as an illustrative example—in ways that reduce environmental and local development tradeoffs in biomass production, and encouraging development of storage capacity (Haszeldine et al., 2018, Torvanger, 2019). CDR incentivization may eventually be linked to carbon trading mechanisms sponsored by the Paris Agreement. These should be structured to avoid shortcomings of antecedent instruments, which initially struggled with false accounting of emissions reductions (Calel, 2016; Honegger & Reiner, 2018). McLaren et al. (2019) suggest measures to ensure that CDR approaches cannot be treated as a substitute for emissions reductions, calling for CDR and emissions policy development to be separated in four areas: targets and timetables, carbon markets, risk-reduction and incentivization, and evaluation.

Guardrails for SRM are similarly pre-emptive, but in the absence of indications of SRM's emergence in policy, these are more speculative. Some focus on state agendas, arguing that multilateral or minilateral arrangements should only allow states undertaking strong mitigation to be involved in SRM decision making (Parson & Ernst, 2013), or introducing a moratorium on deployment, which could set the tone for research into SRM as preliminary and guided by precaution (Parson & Keith, 2013). Others target assessment processes and the scaling up of field-testing in the near-term, arguing for "stage gates" and other mechanisms to forestall path dependencies from research deemed essential to inevitable deployment (Stilgoe, 2015; see also MacMartin & Kravitz, 2019).

5. GOVERNING FUTURITY

We have described how evolving modeling practices are trending toward optimized and "best-case" *projections*—portraying deployment schemes that create both technically slanted and politically sanitized profiles of risk, as well as ideal objectives for CDR and SRM as mitigation-enhancing, time-buying mechanisms for carbon transitions or vulnerable populations. As *promises*, stylized and hopeful projections may legitimize and encourage industrial and political activities built around the inertia of the carbon economy. Some evidence suggests this is the emerging case for certain kinds of CDR, where the prospect of future carbon capture substitutes for present mitigation. Either of these implications is systemic: explorations of climatic futures may already be entrenching certain carbon infrastructures. We point out efforts and recommendations to ensure that this trend does not escalate in the implementation of the Paris Agreement, by creating more stakeholder input and strengthening political realism in modeling and other assessments, as well as through policy guardrails.

We frame these insights as a list of precautionary measures, with an eye to research practice. Although these flow from the article's focus on modeling SRM and CDR, they are generalizable for risk assessment. First, we must not reify projections. In practice, it is easy to default to technical assessment as a proxy for risk, even though it is a starting point under constant reevaluation. We must pay attention to what projections say, but also understand the parameters and assumptions that influence results, as well as who is creating and translating the conclusions for further research and policy. Second, we must pay attention to the selective use of projections. The objectives of deployment as well as depictions of benefit and risk portrayed in modeling assessments graft imperfectly onto existing political and industry agendas. Interests might co-opt a stylized version for pre-existing agendas and gloss over the models' fine print.

Third, we must therefore prize process as much as output. There should be increased efforts at including stakeholders in project design, rather than rely on communication to generate acceptance for results. Fourth, we must prize range as much as optimality. There is a thin line between policy relevance and policy prescription. If modeling produces maps of options, then we might ensure these are not laid out as a gradually narrowing list of optimal schemes. Fifth, we can more clearly establish why assessment is conducted. Is assessment mission-oriented or explorative; science or policy-facing? Being clear on objectives allows communication on the merits and shortcomings of different modes of future-oriented assessment, and how they can complement each other. Finally, we must propose and actively contribute to setting up guardrails. Scientists are foundational actors in establishing terms of debate, but research norms and communication are not sufficient. Climate governance is often frustrated or coopted by the inertia of the carbon economy. Concrete policy measures are needed to prevent SRM and CDR—as ideas or in deployment—from filing in that direction.

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