Climate Imagineering

Practices and politics of sunlight reflection and carbon removal assessment

Sean Jiaming Low

DOI: https://doi.org/10.33540/668

Climate Imagineering

Practices and politics of sunlight reflection and carbon removal assessment

Climate Imagineering

De politiek en praktijk van de evaluatie van zonlichtreflectie en koolstofverwijdering

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de
Universiteit Utrecht
op gezag van de
rector magnificus, prof.dr. H.R.B.M. Kummeling,
ingevolge het besluit van het college voor promoties
in het openbaar te verdedigen op

woensdag 14 april 2021 des middags te 2.30 uur

door

Sean Jiaming Low

geboren op 26 juli 1983
te Singapore, Singapore

Promotor:

Prof. dr. F.H.B. Biermann

Copromotor:

Dr. J.M. Vervoort

This thesis was accomplished with financial support from the Institute for Advanced Sustainability Studies in Potsdam, Germany.

Members of the doctoral committee:

Prof. dr. P.P.J. Driessen
Prof. dr. M.A. Hajer
Dr. A. Kalfagianni
Prof. dr. E. Turnhout
Prof. dr. D.P. van Vuuren

Table of contents

List of common acronyms

BECCS – Bioenergy carbon capture and storage
CCS – Carbon capture and storage
CDR – Carbon dioxide removal
IAM – Integrated assessment modeling
IPCC – Intergovernmental Panel for Climate Change
RRI – Responsible Research and Innovation
SAI – Stratospheric Aerosol Injection
SRM – Sunlight reflection methods, or solar radiation management
STS – Science and technology studies

In the introduction (Chapter 1) and conclusion (Chapter 7), no acronyms are used, in order to aid the general reader. In particular, CDR is referred to more plainly as 'carbon removal', and SRM as 'sunlight reflection'. In the intervening chapters – which all represent published journal articles – the use of acronyms is resumed.

Chapter 1

Introduction

1.1 Context: Sunlight reflection and carbon removal in emerging climate governance

In theatre, we sometimes speak of objects and topics of conversation as 'MacGuffins'. The term – invented by Alfred Hitchcock – refers to an artifact that is central to the plot, but is itself conspicuously absent or weirdly malleable. A MacGuffin is a mirror, a device that illuminates the characters in the drama, the relationships between them and the contexts that shape them, the choices they make, and the unfolding lessons of the story. Beckett's Godot and Tolkien's Ring are famous examples.

The MacGuffins of this thesis are *anticipatory (or future-oriented) scientific assessments of sunlight reflection and carbon removal approaches* – a pair of immature socio-technical strategies to combat climate change. For much of the past two decades, they have been jointly described as forms of geoengineering, or climate engineering, or climate interventions, or climate management. Sunlight reflection methods (solar geoengineering) propose regional or planetary sunshades – by altering cloud properties, or maintaining a global layer of reflective particles in the upper atmosphere – that might cool the planet. Carbon removal (or negative emissions technologies) describes a diverse range of technological, forestry and land-use, or ocean-based sinks that might capture and store carbon directly from the atmosphere. Some sunlight reflection and carbon removal approaches are 'immature' – backed by proof-of-concept, or by sufficient technical knowledge, to arguably be worth further discussion. Some could supposedly be re-purposed from existing ecological management practices or technological systems, making them that much more feasible to implement. Others remain purely hypothetical, confined to modeling calculations and seminar rooms. A very few – mostly forms of forestry management – have been reconceptualized after-the-fact as large-scale carbon removal, and therefore, a kind of deliberate climate intervention. But most sunlight reflection and carbon removal approaches do not, and may never exist as fully-scaled systems. Yet, they already exercise an outsized influence on the proposed direction of climate strategy.

Crucially, it is through expert knowledge and assessment practice that contemporary climate governance is coming to grips with the potentials of a planetary sunshade, or a carbon sink strategy proposed for expansion across terrestrial and marine environments. A common origin story on the entry of these approaches into mainstream conversations on climate action recounts a 'golden spike' moment: a 2006 perspective on the potentials of sunlight reflection by the Nobel Laureate Paul Crutzen, which purportedly dragged that debate out of the academic hinterlands (Crutzen, 2006). Others more readily credit the preceding efforts of engineer and professor David Keith. Alongside a cohort of senior and still-influential earth systems scientists, Keith revived a number of technical concepts out of Cold War-era weather modification, early climate assessment, ocean fertilization, and even terra-forming, and built them into an overarching concept of 'geoengineering' (Keith, 2000). In doing so, many resonant (though increasingly contested) terms of reference were set in play – seminally through the Royal Society's report *Geoengineering the Climate*, and its definition, following Keith, of geoengineering as deliberate and large-scale climate interventions to ameliorate warming risks (Shepherd et al., 2009). Since then, the field has witnessed an escalation of assessments, academic and civic deliberations, international legal interventions, pilot projects and industry innovation, and policy movements across an evolving range of technological and ecological approaches for treating the climate as an object of deliberate management.[1]

The need to inquire after these dynamics is heightened by an emerging context. Sunlight reflection and carbon removal approaches are increasingly becoming normalized by parsing their different feasibilities, timelines, and risk profiles, with an eye to integrating them into policy platforms and governance architectures (e.g. McNutt et al 2015a; 2015b). Sunlight reflection remains a fringe idea in the grander scheme of climate action, but it continues to garner attention as a potential risk management strategy in the face of increasingly fragmented climate (and global) governance. Carbon removal, on the other hand, is swiftly being built into a pillar of post-Paris climate policy, as part of a strategy for developing and enhancing carbon sinks to meet 'Net Zero', or commitments towards carbon neutrality by mid-century informed by the temperature goals of the 2015 Paris Agreement. A decade ago, when these two suites of approaches were more commonly thought of by experts as forms of geoengineering or climate engineering, there was more pervasive critique of a scale of transboundary intent and action, some manifestation of the Anthropocene's zeitgeist, or of novel and desperate climate strategies that merit common precaution (e.g. Hamilton, 2013). Where there was once a sense of the historical, ethical, and contingent, there is increasingly an emphasis on the technical, procedural, and manageable. How did this come to be? What are the implications for future politics and planning?

At the same time, to speak of sunlight reflection and carbon removal in policy-facing frames, or even broadly as the enterprise of 'engineering' the climate, misses a longer and wider arc. These are just the latest entrants to the landscape of sociotechnical proposals for addressing climate change – from renewable and nuclear energy, to shale gas and biofuels as 'bridging' options, carbon capture and storage, and walls guarding against sea-level rise – currently categorized as forms of mitigation and adaptation. Many budding climate strategies share this in common: to gain credence, their potentials have to be assessed as if they were implemented at scale, with climatic and socio-economic effects projected and framed to be meaningful, sustained, and ameliorative. Do the politics of science readily observable in sunlight reflection and carbon removal assessment have wider parallels in climate governance?

It is vital to maintain watch over these knowledge politics. We must be wary of allowing expert assessments to be black-boxed, and take for granted how established wisdoms – clean 'facts' and leading implications – on game-changing, planet-spanning strategies are pieced together at workshops and conferences. And we must be doubly cautious of how the potentials of sunlight reflection and carbon removal are established in a post-Paris and post-Covid-19 world, as we inch into a multi-polar landscape starved for economic recovery, with fragmented governance architectures strung amongst increasingly systemic governance problems.

[1] There are many nuances to this history, and I recommend the following accounts. Stilgoe (2015) is a critical reading of the construction of risks and potentials in sunlight reflection through modeling and mechanics testing. Morton (2015) is a publics-facing account of 'geoengineering' – as disparate technologies as well as eco-modernist concepts – in the Anthropocene. Blackstock and Low (2018) is a community effort: a curation of working papers and commentaries gathered between 2012 and 2016. Buck (2019)'s *After Geoengineering* combines fictional visioning of engineered climates later this century with a geography-grounded mapping of today's knowledge politics.

1.2 Aims and significance: Anticipatory and expert-driven assessment

In this thesis, I call attention to how *anticipatory, expert-driven assessment practices shape societal deliberations, contexts, and expectations – and vice versa*.

Why does this formulation matter? Research into the impacts of climate change, as well as of strategies to reduce them, is *anticipatory,* in that decisions in the present have to be taken on the basis of projected futures in scientific assessment. *Experts* are in the forefront of this process, setting and contesting foundational terms of debate, translating and gate-keeping for policy and public audiences, and advocating for further (kinds of) research, funding, and governance. Because sunlight reflection and carbon removal approaches are largely immature or imaginary, how they might be deployed, and what challenges they pose, have to be projected, imagined, and communicated by multidisciplinary networks of scientific experts with disparate views on the state of climate governance, further filtered through a range of futuring assessment practices – among others, climate and economic modeling, engineering schematics, analogies, surveys, deliberative engagements, and foresight and gaming.

No assessment can be comprehensive or definitive, but that is the very point. Engagement with the future is not politically neutral. Evidence is made, and slanted, through the expertises, biases and choices of researchers and technologists who are the leading thought entrepreneurs in an evolving debate. Anticipatory assessments emphasize different baskets of risk and benefit, and thereby contain embedded claims – sometimes implicit, sometimes instrumental – on the viability of sunlight reflection and carbon removal. In turn, they influence the proposed direction of scientific and policy agendas. This raises key questions about the role of scientific knowledge in shaping what can be known about emerging technologies that could potentially scramble long-established wisdoms about how to address climate change.

What is the scientific and societal relevance of my inquiries? I contribute to an emerging literature that maps the knowledge politics of 'geoengineering' within climate governance, synthesizing principles and insights from literatures on global environmental governance, science and technology studies, and sociologies of future-making (sections 1.4.1 and 1.4.2). My particular contributions here: I establish a synthesizing treatment of diverse assessment practices (from simulative modeling to engagement-based foresight) as comparable forms of anticipation; and I show the interplays in anticipatory practice between choices at the project- and network-level (agency), and contexts and conditions at the regime- and society-level (structure). I then rely upon the 'responsible research and innovation' framework for participatory and reflexive engagement to design bridging exercises between different communities of anticipatory practice (section 1.4.3). My contributions here: I engage directly with highly-invested cohorts of expert knowledge-producers in governance processes (rather than mini-publics), and in doing so, contribute to entrenching reflexive practice 'at the source'.

Furthermore, the structure of my thesis directly links critical analyses of anticipatory practices to forward-facing engagement. This structure is a particular contribution, and it integrates three movements. The first movement is from *analytical to engagement* work, using critical mappings of the knowledge economy to contextualize and inform bridging activities amongst experts and stakeholders. The second is from *retrospective to generative* work – from backward-looking or real-time analysis of how knowledge is constructed by others, to activities that use the future as a sandbox to generate new knowledge, and that has in turn shaped assessments. The final direction goes from *general technological categories to specific approaches*, which allows a more finely-grained engagement with the wider politics of planetary interventions, and then to those of particular approaches and their associated expert networks. I elaborate on these in explaining the thesis design, and the sequencing of my chapters (section 1.5).

In doing so, I see this research as more than a mapping of knowledge politics of expert communities, practices, and politics; it is a translation of that intellectual economy for activities that seek reflexive and forward-looking reform. It also reflects a journey I have undergone as part of these processes: over the course of the chapter studies, I go from being an invested observer or active participant in the politics of assessment and expertise, to (ostensibly) stepping out of them in bridging and engagement exercises intended to break down political biases and disciplinary siloes.

Returning to that theatrical device: If the MacGuffins – the *what* – are scientific assessments, and framings of means and ends, costs and feasibilities, threats and opportunities that benchmark progress or signal for retreat, these illuminate the *how* – practices and processes of knowledge-making; the *who* – creators, translators, and users of knowledge; the *where* – stage of development, research network, locale; and the *why* – the political choices and contexts that underpin scientific assessment. How these suites of technologies are currently projected and entrenched in public discourse, industry, and governmental policy may reinforce a spectrum of options between perpetuating and re-orienting the carbon economy. The objective of this work is therefore to examine how these futures are constructed and claimed, as an underlying base of knowledge upon which climate strategies in coming years will be built.

1.3 Research questions and structure

I inquire after three research questions.

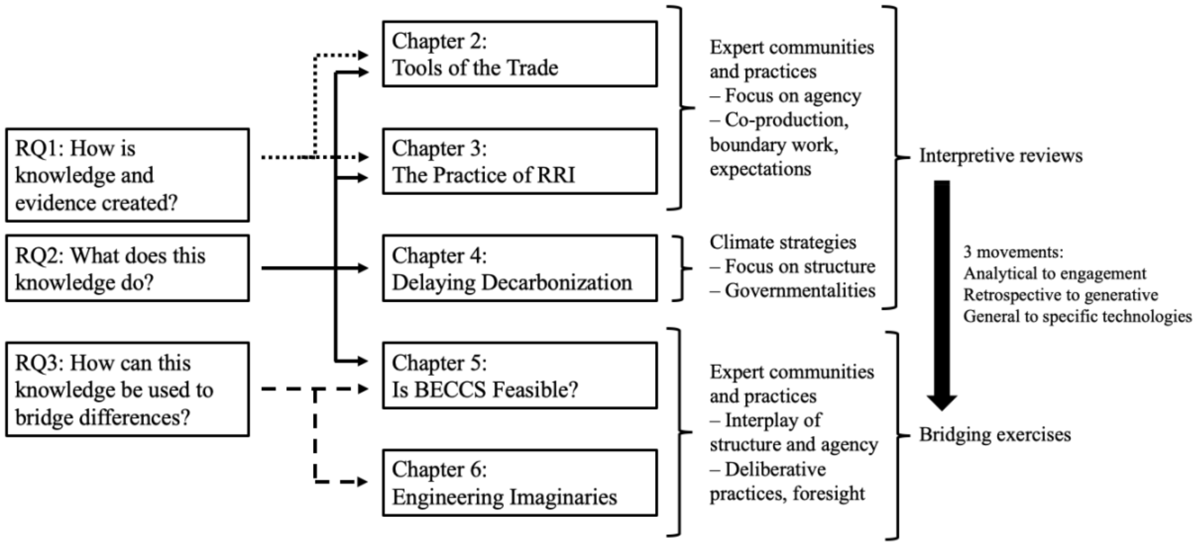
Firstly: How is knowledge and evidence about sunlight reflection and carbon removal created? I focus on scientific expert networks in the global North, exploring how their futuring practices reflect different rationalities and epistemologies, how these emphasize different risks and challenges, and how they speak to different scientific, civic and policy audiences. This relies on concepts and frameworks – 'co-production' and 'boundary work' in 'regulatory science' – from the meeting of global environmental governance with science and technology studies (section 1.4.1 and 1.4.2), and is the subject of Chapter 2 and Chapter 3.

Secondly: What does this knowledge do? I examine how futuring practices set resonant depictions of sunlight reflection and carbon removal potentials in play, and emphasize certain modes of assessment over others. Bodies of knowledge and kinds of knowledge-making call for different directions in research and policy, and actively – if imperfectly – steer climate governance in their image. Here, I also bring in critical sociologies of how rich and forceful depictions of the future are conceived of – and how they become politically active – through expectations, imaginaries, and governmentalities (section 1.4.2 and 1.4.2). These inquiries are tackled in Chapter 2, Chapter 3, Chapter 4, and Chapter 5.

Thirdly: How can this knowledge be used to bridge differences? From understanding this knowledge economy, I engage with different expert networks and knowledge types to use futuring practices as platforms for deliberation and mutual learning, as well as for exploring directions for research and policy. I rely on anticipatory and deliberative practices for the governance of emerging fields of science and technology (section 1.4.3), and these are the basis of the bridging and forward-facing engagements of Chapter 5 and Chapter 6.

Section 1.4 lays out the territory to which this thesis contributes. My work overlaps three areas: the evolving arc of environmental governance in the Anthropocene, analytical frameworks from science and technology studies, governmentality studies, and sociologies of the future, and the futurity- and stakeholder-facing activities undertaken by technology governance frameworks. Section 1.5 lays out the objectives, sequencing, and relationships between chapters, as well as the research methods undertaken. Below, Table 1.1 visualizes the thesis structure with an emphasis on simplicity, showing links between the research questions, the chapter studies, and the key aims, topics, and methods thereof. The reader can refer back to it for clarification as we progress through this structure in greater detail.

Table 1.1 Thesis structure



Column 1 describes the research questions (section 1.3), which underpinned by theoretical literatures in section 1.4. Column 2 lists the chapters. Column 3 and 4 describe the aim and topic addressed, the theoretical literature relied upon, and the method or approach designed to inquire after it (section 1.5).

1.4 Research territory and gaps

1.4.1 The knowledge politics of climate and environmental governance

I see myself foremost as a global environmental governance[2] scholar, with a methodological focus on anticipatory (or futurity-oriented) assessment and planning, and a topical interest in emerging climate strategies of a sociotechnical nature. My orientation towards these topics – and thinking on sunlight reflection and carbon removal as case studies – has benefited from the convergence of several literatures.

[2] I use 'global environmental governance' as an imperfect catch all for the evolving assessment and governance of our human civilization, embedded within - and forcefully changing - natural environments. The field itself, and the names by which it is known, are changing to reflect understandings of systemic relationships between the human environment and myriad other issues of global governance. 'Earth system governance' is a resonant attempt to re-conceive this landscape. There are many others, and the result may well be a 'conceptual pluralism' (Biermann, 2020).

Global environmental governance has always had a strong focus on architectures: regimes, institutions, markets, actors, and agendas (Biermann, 2016; Biermann & Kim, 2020, eds; Biermann & Pattberg, 2008; Dauvergne & Clapp, 2016; Gupta, 2010). Waves of exchange with critical disciplines – science and technology studies is a key example – have opened up avenues for investigating the rationales and processes by which climate change and other environmental governance issues – as problems and adjoining solutions – are constructed (Aykut, 2016; Hulme & Mahony, 2010; Lahn, 2020; Lorimer, 2017; Lövbrand et al., 2015; Miller, 2004; Stripple & Bulkeley, 2014; Turnhout et al., 2007). Science and technology studies foregrounds the oft-hidden politics of knowledge construction in global governance, and ties governance studies to longer traditions of post-structuralism and meaning-making in politics, culture, and language.

These exchanges, happily, have created mutual benefits. Global environmental governance studies have become sensitized to the hidden politics and shaping influences of 'knowledge-making for decision-making' (Miller & Wyborn, 2018) – from fisheries stocks, to biodiversity metrics, to integrated assessment modeling – to nuance governance- and solutions-oriented work. Meanwhile, critique-focused STS gravitates increasingly towards engaged practice in contemporary challenges (Sismondo, 2008; Sarewitz, 2016) and applied frameworks of governance (Guston, 2014). My thesis operates within this growing space, and is representative of efforts to balance the animating spirit of activism in global environmental governance studies with that of reflexivity and responsibility in science and technology studies (Biermann, 2016; Dauvergne & Clapp, 2016). Understanding the knowledge economy of climate and environmental change has to be a means to improving it.

If climate and environmental governance form the ground for my investigations, science and technology studies provide my orienting and analytical frameworks. I treat sunlight reflection and carbon removal as *emerging sociotechnical systems*: proposals that combine the hardware of immature, unscaled technologies with the software of societal contexts, beliefs, and choices. This term is used across a range of fields and theories – from schools within science and technology studies, to innovation studies, to discourse analysis – to describe how novel technologies are diffused (Sovacool et al., 2017). Given my interest in the politics and power relationships reflected in scientific practice, I move away from innovation-oriented 'transitions' work (e.g. Geels & Schot, 2007), and towards traditions that treat the creation of scientific knowledge and procedures – and the technological applications that rely upon it – as social processes mediated by aims, cultures, and paradigms (Sismondo, 2008). Science and technology studies contain other hallmarks that have influenced my work: that scientific controversies are opportunities for re-examining how previously black-boxed knowledge can be reformed, and the value of an embedded approach in the foundational stages of a field's knowledge making ('in the laboratory', so to speak).

Perspectives on the politics through which science is 'settled and unsettled' are diverse, ranging from the actor- and interest- oriented 'social construction of technology' framework (Pinch & Bijker, 1984), to the focus on fluid relationships between human and nonhuman (things, concepts) pioneered by 'actor network theory' (Latour, 1987). Without prejudice to these frameworks, I align loosely with the *'co-production'* tradition (Miller & Wyborn, 2018), which argues that actors, from expert networks to broader polities, design science and technology to mirror what they desire in nature and in society. In this sense, expert judgments on the feasibility and desirability of sunlight reflection and carbon removal are entwined with normative beliefs on the state and direction of climate assessment and governance, and become active through the formation of identities, institutions, discourses, and representations that mediate what 'facts' become accepted or hidden from view (Jasanoff, 2004).

Co-production is also a pragmatic theory – Jasanoff (2004) terms it an 'idiom' – where the construction of science is a fluid interplay between *structures* of political rationalities and disciplinary training, and *agency* of personal choices and collective agendas. Co-production is in conversation with the crucial concept of 'boundary work', where the terms of debate are defined by (expert) communities in ways amenable to their agendas and research practices (Gieryn, 1983). Boundary work is central to my chapters, and I will return to it in-depth in the conclusion (section 7.3.1). I focus on pre-policy expert activities described by Gieryn (1983) as 'mandated science', and Jasanoff (1990) as 'regulatory science': the production of scientific assessment to inform public decision-making. Some sunlight reflection and carbon removal assessment processes are already tied into established science-policy interfaces. Others aspire to a closer relationship with decision-making structures deemed relevant – Flegal (2018) dubs this 'proto-regulatory science'. This are activities where – paraphrasing Hoppe (2005) – politics are scientized, and science is politicized. Communicating with stakeholders, making decisions, and crafting governance rely on the upholstering provided by expert assessment; meanwhile, assessment is crafted to face different audiences and processes, containing overt judgments and implicit biases, and with instrumental and accidental effects.

The knowledge politics of sunlight reflection and carbon removal, or climate engineering more broadly. is a research gap that remains open. Still, there is movement within it. An illustration: in the past three years, a cohort of long-standing colleagues have published their own theses on these topics – with varying emphases on parts of the puzzle. Flegal (2018) and Oomen (2018) are (partly) ethnographic examinations of the politics of expertise. Möller (2019) is interdisciplinary, examining a mix of discourses, institutions, and assessments to point out how kinds of knowledge and power dynamics are produced and reinforced; Boettcher (in preparation) focuses in-depth on discourses surrounding various governance sites, with an eye to recognizing how to break the resilient modes of thinking that make only certain kinds of governance possible. McLaren (2018) and Buck (2017) highlight the knowledge of marginalized communities; the former with a unifying focus on ethical inquiry and climate justice, and latter more broadly on how the human environment is conceived of and planned for in the Anthropocene.

There are clear overlaps between all these works, and my own. Nevertheless, I claim several distinctive emphases. Firstly, I contribute a coherent structure that links critical mapping of expert communities to forward-facing engagement that attempt to bridge their differences (section 1.2). Again, this reflects an understanding of myself as part of the expert communities and assessments that I examine, and a translation of their politics, practices, and even power dynamics for use in reform-minded engagements. My other contributions – a synthesizing treatment of diverse assessment practices as forms of anticipation; the interplays between agency and structure, and project- and society-levels in anticipatory practice; and cultivating reflexivity through engagement with expert networks – unfold in the following sections, where I detail further grounding literatures on sociologies of the future (section 1.4.2), and anticipatory and deliberative research practice (section 1.4.3).

1.4.2 Sociologies of the future

A characteristic common to sunlight reflection, carbon removal, and other sociotechnical climate strategies is their unfinished nature. Many are partially scaled (e.g. certain renewables), some embody a temporarily-stalled 'revolution' (shale gas), while others remain at the project level (e.g. carbon capture and storage, and carbon removal) or exist only in assessments (e.g. sunlight reflection). Yet, many emerging strategies play disproportionate, reified roles in climate discourse and policy. Futures are *performative* – a layman's synonym might be 'sticky' – in that they shape incoming science and politics in their image. At the same time, these shaping aspirations are never perfectly realized: futures are highly contested within expert networks, and graft selectively onto existing infrastructures and agendas in policy, industry, and civic life.

This brings us into contact with literatures on the sociology of 'expectations' (Brown et al, 2000; Borup et al., 2006), 'futures' (Selin, 2008; Adam & Groves, 2007), 'visions' (Grin & Grunwald, 2000), and 'vanguard visions' (Hilgartner, 2015) which highlight the forcefully *promissory* nature of projections of immature technologies in their finished state. Many of these frameworks draw upon cases of novel technoscience; others on environmental issues (Granjou et al., 2017) or a wider range of global governance challenges (Anderson, 2010). Each of these 'creatures of the future tense' (Selin, 2008) carries nuances on the extent to which the future can be known, the actors, locales and dynamics by and within which futures are generated, the timescale over which they exercise claims, the probability or plausibility of their occurrence, and the intent for which they are created (for an excellent categorization of rationales governing different practices of futuring, see Muidermann et al., 2020). Exploring the future, then, is also an exercise in claiming the future (Selin, 2008). Expertise and evidence are underpinned by political contexts and judgments; they also have political effects in privileging certain sociotechnical and political options in both 'de facto' governance (informal but forceful research conventions) and formal policy (Gupta & Möller, 2018; Boettcher, 2019).

I expand upon the deployment of sociologies of futures in studies on sunlight reflection and carbon removal, accounting for two kinds in the same space of investigation. The first is captured by the 'expectations' literature, in which futures are more instrumental and driven by agency and choices, and situated at the level of scientific networks and emerging pilot projects and demonstrations (Brown et al, 2000; Borup et al., 2006). Here, stylized depictions and discourses of a technology's future usage act as advertisements and warnings, with coherent storylines of progress benchmarks, benefits and risks, and facilitative or regulatory mechanisms. These are deployed to hype – or alternatively, to retard – the development of a technology at its earliest stages (ibid). The second is captured by adjoining literatures on 'sociotechnical imaginaries' (Jasanoff & Kim, 2015, eds.) and governmentalities (Stripple & Bulkeley, 2014, eds; Lövbrand et al., 2009; Bäckstrand & Lövbrand, 2006 and 2016). Imaginaries (a recent science and technology studies concept) and governmentalities (a Foucauldian concept with a richer genealogy), are not identical; the former recalls Jasanoff's co-productive idiom, while the latter leans towards the conditionings of structure and hegemony. Yet, both see the representation of and acting upon a phenomenon as highly entwined; describing ensembles of an overarching, normative rationality (a political or societal logic) manifested in practices, instruments, and institutions in emerging techno-science (Jasanoff & Kim, 2015, eds.) or environmental governance (Stripple & Bulkeley, 2014, eds). In these frameworks, futures become politically active in more implicit and systemic ways. Interplay between structures and agency in scientific assessment is emphasized, and activities are dispersed throughout levels of polities, societies, and paradigms. My chapters explore the interplays between project- and society- level futurings, and between overarching structural influences and the agency represented by research choices, to show that what experts believe about controversial climate strategies, about priorities for assessment, about proposals for development or prohibition, and about the future of climate governance are all deeply entwined.

Another area where I focus is the study of particular expert networks, where politics and assessment practices are co-produced. Studies have examined authorship networks (Oldham et al., 2014), or research programs (Flegal, 2018; Oomen, 2019) and organizations (e.g. NGOs, van der Linden, 2018), as well as framings and discourses that marshal actors around shared understandings and goals (Anselm & Hansson 2014a; 2014b; Boettcher, 2020). To these, I add another dimension of research practice, through which actors of like mind and intent filter their development of future-oriented scenarios. These modes of assessment surrounding sunlight reflection and carbon removal act as a shorthand for different normative underpinnings, aims, epistemologies, and communities of practice (Lave & Wenger, 1991; Haas, 1992). Here, I particularly add to critical studies of knowledge communities relying on technical modeling (Wiertz, 2015; van der Sluijs, 2002; Corbera et al., 2017; Cointe et al., 2020; Heymann & Dahan Dalmedico, 2019; Saltelli et al., 2020) and deliberative engagement (van Oudheusden, 2014; Burget et al., 2017; Ribeiro et al., 2017) to construct the potentials of novel sociotechnical strategies.

1.4.3 Anticipation, deliberation, and planning

In recognizing dynamics set in play by conceptions of the future, an opportunity emerges for researchers: the move from analysis to engagement. This is the objective of related frameworks – *anticipatory governance* (Guston, 2014; Sarewitz, 2016) and *responsible research and innovation* (Stilgoe et al., 2013) – that maintain dialogue between science, society, and policy on the means, ends, and governance of novel technologies. These frameworks are part of twinned 'anticipatory' and 'deliberative' turns towards society-facing work in science and technology studies, connecting *critical interrogations* of an emerging technology's knowledge economy to *deliberative engagements* that seek to repair shortcomings in representation (marginalized demographics and perspectives), procedure and epistemology (types of knowledge and modes of assessment), and outcome (a lack of alternatives in imagining the future, or in decision-making).

A wide array of methods are used (climate-fiction writing initiatives, engagement workshops, foresight-based scenario-building, 'serious' games) to design experimental futures with stakeholders, as sandboxes within which to provoke mutual learning, investment, and reflection on diverse plausibilities and options for response (Chilvers & Kearnes, 2019; Bellamy, 2016; Hajer & Pelzer, 2018; Milkoreit, 2017; Selin, 2008; Vervoort, 2019). Engagement has even come to harness and make accessible highly technical tools, using – for example – climate and economic models as learning spaces

(Salter et al., 2010). Rather than stick to analysis of a particular kind of futuring (for example, modeling), I engage with and translate a wide range of anticipatory approaches deployed throughout research – earth systems and integrated assessment modeling, thought experiments and analogies, deliberative engagement, and foresight-based scenarios. I do so in order to build cross-disciplinary knowledge of how different expert communities understand futurity (see section 3.2), and in particular, to seek synergies in objective and epistemology that had previously been hidden by academic tribalism.

In anticipatory governance and responsible research and innovation, the objective of engagements is to 'open up societal appraisal' (Stirling, 2008) or strengthen a mode of 'slow science' (Stilgoe, 2015), where procedural questions of inclusiveness and reflection surrounding controversial new technologies are prized above creating 'actionable evidence' (Owen, 2014) for better incorporation into policy processes. Moreover, it offers opportunities for a deeper recognition of how research politically shapes the fields that academics are supposed – in more traditional thought – to be neutrally assessing. Deliberation and anticipation dovetail with ambitions towards 'transdisciplinarity' (Lang et al., 2012) that has come to inform many scholarly fields, including global environmental governance (Biermann, 2016). I align fully with these aims, and see deliberative, anticipatory, and transdisciplinary work as bridging people and scales: between multiple creators, translators, and users of knowledge, as well as between global kinds of knowledge and knowledge 'situated' or 'embedded' in particular localities, cultures, sectors, and institutions (Turnhout et al., 2013; Chilvers & Kearnes, 2019). These activities navigate kinds of academic responsibility: between the immediacy of tackling urgent environmental, societal, and technological issues, and remaining open to multiple modes of knowledge and action (Biermann, 2016; Sarewitz, 2016).

In these exercises, I emphasize expert networks – and other relatively well-defined communities of common interest and practice – more so than publics. This is due to my interpretation of 'deliberation', and how my work is thus influenced. 'Mini-publics' of randomly selected individuals are often – though not exclusively – treated as the ideal engagement group, able to endogenously and collectively generate insights that challenge technocratic perspectives (Niemayer, 2014). I share this as an aspiration. There is a need to structure dialogue spaces on a societal scale, as deliberation is a collective skill and culture to be reinforced in education, media, and governance (e.g. Lenzi, 2019). Guston (2014) emphasizes that these activities are – referencing a joke about how to get to Carnegie Hall – a matter of 'practice'. I sympathize with efforts to expand the co-productionist idiom (Jasanoff, 2004; Miller & Wyborn, 2018) into deliberative engagement practices, where participating publics are treated neither as anonymized and rational agents (Habermas, 1984) nor as vessels of a preceding discourse (Mouffe, 2005), but as novel collectives created in the moment (Chilvers & Kearnes, 2019).

At the same time, I do not believe that the entrenched structures that condition human beings – from cultural identities and institutional agendas, to skill sets and accessibility to information – are so easily overcome in the course of deliberative activity (Lenzi, 2019; Lövbrand et al., 2011; Sanders, 1997; Turnhout et al., 2010). My own engagement work, therefore, leans more into the conditionings of structure, where I conduct bridging exercises between invested actors and networks with traceable political stances, sectors, affiliations, and disciplines – rather than mini-publics. I start with the assumption that invested actors impose structural politics on discussions of what is at stake, and that tracing and confronting those frames and agendas is key to any robust deliberative outcome (Hajer & Versteeg, 2005). However, the goal is still to generate mutual learning between invested positions, perhaps even a legitimate outcome negotiated amongst participants. Structure cannot be utterly deterministic, and the point of mapping the conditionings imposed by expertise, institution, or political affiliation is to overcome them. This I see as in line with activist strands of global environmental governance research, as well as critical traditions of science and technology studies, in maintaining that 'it can be otherwise'.

I conclude this retracing of research territory by signalling intent for future work. In this thesis, I cover the meaningfully constitutive work done by expert communities in sunlight reflection and carbon removal assessments. But what is next? The question of 'Whose nature is being represented?' extends beyond sunlight reflection and carbon removal assessments; even beyond climate assessment. Technical and technocratic kinds of expert knowledge are thought to increasingly bound research on the global environment. The environment is argued to be metricized into something uniformly governable, and governance is conceived of as managerial choices between technologies (and technological fixes, Weinberg, 1967) rather than between livelier, catalytic re-imaginings of global society (Lövbrand et al., 2015; 2020; Castree, 2016; Vervoort et al., 2015). To this, others add the curiously unrelatable nature of global knowledge, particularly in climate change – the 'view from everywhere' untethered to everyday lives and livelihoods (Hulme, 2010; see also Rayner & Prins, 2007). It is our opportunity to connect local perspectives to the global imaginary, and situated understandings to overarching goals. We live in times of polarized politics and fragmented governance, but global issues are no less systemic in scope, and we must maintain the architectures needed to address them (Biermann & Kim, 2020, eds). If global knowledge has become 'brittle' (Hulme, 2010), then we must also ensure that a turn to situated knowledge does not become parochial. This is a gap waiting to be filled, and I revisit it in the thesis conclusion.

1.5 Thesis design and methods

1.5.1 Three directions of travel

In this section, I describe the overall thesis design: the contents of each chapter study, the relationships between them, and the data-gathering (or engagement) and analytical methods they deploy. It is traditional to have separate sections that introduce the chapter sequencing and the methods they use; what follows will combines both. As I prefaced in describing the aims and significance of the thesis (Section 1.3), I introduce a framework that connects a series of critical mapping and interpretation to bridging engagements. Aims, methods, and sequencing flow naturally from this design (see Table 1.1 in Section 1.3). Hence, rather than attempting a synthesized, thesis-wide overview of how I conduct my analyses, I lay out the objectives and research methods taken chapter-by-chapter, alongside an explanation of the order and relationships between chapters, and how these reflect an overall design and narrative.

Before beginning, I re-present my research questions to better orient the reader. Firstly, how is knowledge and evidence about sunlight reflection and carbon removal created? These inquiries rely on exchanges between science and technology studies and global environmental governance on co-production and boundary work, and involves Chapters 2 and 3. Secondly, what does this knowledge do? This implicates sociologies of the future, and is the subject of Chapters 2 to 5. Thirdly, how can this knowledge be used to bridge differences? This makes use of anticipatory and deliberative frameworks, and is deployed in Chapters 5 and 6.

My *objects of study* are future-oriented artifacts contained in scientific assessment of sunlight reflection and carbon removal. These might be scenarios and discourses, and expectations and imaginaries embedded in academic papers, policy documents, technical modeling, and narratives and analogies crafted for popular consumption. However, I also treat these artifacts as reflections of the actors and contexts, and agencies and structures, that construct and contest them as outputs of assessments argued to be credible and legitimate. Hence, my objects of study are extended also to research practices and epistemologies, knowledge networks and communities, and overarching ensembles of rationalities and activities on the ideal shape of scientific assessment, stakeholder communication, and policy-making, climate and environmental governance, and human-nature relationships. I see the theatrical device of 'MacGuffins' as an anchor for how I regard future-based evidence – as resonant depictions of future implementation and associated challenges, but also as reflections of representation (who is missing), procedure (who makes the decisions), epistemology (how do experts know what they know), and outcome (what is emerging now in the research and governance landscape, and what alternatives are closed down).

My frameworks of *data gathering and analysis* are in the post-structural and interpretive tradition, where investigations of how meaning is made of societal phenomena is investigated qualitatively (Bevir & Rhodes, 2016, eds). Interpretive work, in turn, can be operationalized through a vast array of (mixed) methods, from meta-analyses to stakeholder engagements. As mentioned, I will outline and justify these chapter-by-chapter. Before going into those specifics, I point out my studies as a whole are underpinned by what my colleague Holly Jean Buck in her own thesis (Buck, 2017) calls 'background methods': a deep immersion in the scientific networks that I map and engage with. This goes beyond being an 'embedded researcher', parachuted temporarily into knowledge-making processes. Since 2010, I have worked for two research institutes on the science and politics of sunlight reflection and carbon removal, and as a global governance researcher, was a founding member of the climate engineering program at the Institute for Advanced Sustainability Studies in Potsdam. I have grown up in the academic life with a cohort of scholars and practitioners who are by turns my colleagues and my objects of study. With particular regard to deliberative and anticipatory branches of work, I have actively participated in what my thesis observes.

The overall thesis design, then, *reflects three directions* that order the chapters and reflect their aims and methods. The first is a movement from *analysis to engagement* – from mapping the knowledge economy to actively engaging with that economy in order to bridge differences and fill gaps in the kinds of knowledge represented. The second is a move from traditionally *retrospective to generative* social science, where knowledge is created via stakeholder engagements and futuring approaches such as modeling or foresight. Both of these are linked – they represent moves from informing societal debates to forming them. The third movement relates to how sunlight reflection and carbon removal are treated topically – I move from discussing them collectively as forms of climate engineering (or large-scale and deliberate interventions in the climate system), or as the latest modes of novel, immature sociotechnical strategy to address climate change, to their separate suites as novel forms of sunshades and carbon sinks, to individual approaches of bioenergy carbon capture and storage (a kind of carbon removal) and stratospheric aerosol injection (a kind of sunlight reflection). By moving from *general to specific* categorizations, I am able to show a greater sensitivity to the actors, contexts, practices, and politics surrounding each.

1.5.2 Interpretive reviews provide critical mapping

The beginning chapters, *Tools of the Trade* (2) and *The Practice of Responsible Research and Innovation* (3), fulfill three purposes. Firstly, they contain the literature reviews that commonly preface academic studies. *Tools of the Trade* (2) is on the broad field of 'future-making' approaches in climate engineering, casting a bird's eye view over earth systems and integrated assessment modeling, game theoretical modeling, deductive modes of social science, and anticipatory and deliberative modes of stakeholder engagement and foresight-based scenarios-building. This chapter represents a *narrative review* – highlighting key trends and directions in futuring practice, but perhaps at the expense of being completely systematic and exhaustive. *The Practice of Responsible Research and Innovation* (3) hones in further upon practitioners of 'responsible research and innovation' and 'anticipatory' frameworks for technology governance, and forms a more *systematic review* of a network of actors who have been comparatively critical of carbon removal's and sunlight reflection's prospects, and whose practices and politics are under-assessed in the literature in comparison to modelers, technologists, and perceived enthusiasts.

However, I do not deploy these reviews as matter-of-fact listings of studies that have been conducted in the same tradition, before moving on to critical analysis in later items. The second purpose of these reviews is to act as *interpretive* analyses of the knowledge landscape. *Tools of the Trade* (2) traces research practice as shorthand for communities, epistemologies, activities, and motivations regarding climate governance that are mutually constitutive. It creates a narrative of future-making in climate engineering as an evolving history of how risks are constructed by different philosophies and practices of assessment, contrasting a disproportionately influential 'deductive' mode that produces technically-slanted actionable evidence for policy-making with a 'deliberative' mode that seeks to puncture technocracy in science and technology issues of societal import. *The Practice of Responsible Research and Innovation* (3) applies a critical lens to this 'deliberative' mode as networks of social science scholars in 'responsible research and innovation'. Drawing upon a review of activities in responsible research and innovation, we identify tensions in their practice, how activities form or inform choices, the positionalities of practitioners, and ways in which activities enable or disable particular climate interventions – for example, implicitly favouring carbon removal as opposed to sunlight reflection. There is an attempt to critically assess responsible research and innovation by its own standards and traditions, as an outgrowth of applied science and technology studies. The final purpose of these 'interpretive reviews' is to therefore not only map these processes, but use them to background the engagement-based activities that follow, by pointing out shortcomings in representation (who is missing), procedure (who makes the decisions), epistemology (how do experts know what they know), and outcome (what is emerging now in the research and governance landscape, and what alternatives are closed down).

The next chapter, *Delaying Decarbonization* (4), is a *systematic* and *interpretive review*: a landscaping analysis of immature climate strategies that emerged during an era (2005-2015) centered around the 2009 Copenhagen Accord: carbon capture and storage, REDD+, next-generation biofuels, shale gas, short-lived climate pollutants, carbon removal, and sunlight reflection. However, this chapter represents three departures from the previous pair of chapters. Firstly, there is a move from treating conceptions of futures through assessments as relatively instrumental, project-level expectations, to governmentalities operative at the level of global climate policy over decades. Second, I situate sunlight reflection and carbon removal not as kinds of climate engineering (the common macro-framing of the two suites), but within a longer and wider arc of emerging sociotechnical strategies to address climate change. This sets up the third movement, which emphasizes the conditioning influences of structure over agency (the epistemologies, biases, and choices of scientific communities). In this case, the structure was the resilient neoliberal environmentalism of the Kyoto Protocol era. Specifically, I find that Copenhagen era's sociotechnical strategies had to navigate the increasing fragmentation of the global regime, while presenting numerous outlets for signalling climate ambition that delayed deep-lying decarbonization. The intent is to show that these emerging strategies, for all their different technical specifications, file into comparable and often well-worn political usages. If my other chapters contain a normativity towards our agency to shape the future, this chapter reminds us that we continue to combat constraints at systemic levels.

1.5.3 Bridging exercises emphasize anticipation and deliberation

The final pair of chapters – *Is Bioenergy Carbon Capture and Storage Feasible?* (5) and *Engineering Imaginaries* (6) – are *anticipatory and deliberative engagements* between expert communities and networks pinpointed in earlier mapping exercises (chapters 2 and 3, particularly). These chapters hone in on the interplay between structure and agency. Expert communities are conditioned by discipline, institution, and shared beliefs about the state of climate governance; they impose structural discourses on conversations with those not of their tribe. At the same time, deliberation offers an opportunity for rising above those constraints and achieve those 'Eureka' moments sought by engagement practitioners. To achieve greater specificity in engaging expert communities, these chapters move from sunlight reflection and carbon removal as macro-categories to specific options.

Is Bioenergy Carbon Capture and Storage Feasible? (5) focuses on an immature carbon removal approach projected in integrated assessment modeling that arguably acts as a large-scale stop-gap for making the ambitious temperature targets adopted by the Paris Agreement appear achievable. The chapter consists of *multiple rounds of survey and semi-structured interviews* between senior members of an integrated assessment modeling community and a multi-disciplinary group of critical experts. Using the concept of boundary work, I show that how modelers and critics calculate the feasibility of bioenergy carbon capture and storage (and other immature, unscaled sociotechnical options) is closely entwined with how they think about the proper relationship between modeling projections and global climate policy, between science and decision-making more generally, the freedom of scientific inquiry in politically-charged circumstances, and the necessity of reform to integrated assessment modeling work or to the Intergovernmental Panel for Climate Change. In other words, expert communities envision, conduct, and propose improvements for scientific assessments in ways that defend their epistemic authority. At the same time, by asking participants to explicitly engage with each others' terms of reference and perceived motives, the study also generated avenues for a common understanding of the value of future scenarios.

Engineering Imaginaries (6) is based on a year-long project that brought together scholars and practitioners engaged in conversations on the governance of stratospheric aerosol injection, a particularly debated planetary sunshade scheme. Again, the chapter leaned into structure – participants were chosen for a combination of disciplinary background, as well as leanings on stratospheric aerosol injection that could be discerned from the publication record. However, room was then made for examining agency through deliberation. Based on three workshops, this study deployed *foresight-based scenario building* to generate four alternative futures leading to 2030, each embodying different challenges associated with developing stratospheric aerosol injection. These scenarios provided contexts for designing governance systems for these challenges, and for the evaluation of options that might be robust against as many contingencies as possible. This chapter attempted to balance several aims. The first was to navigate a tension in foresight practice between providing a platform for communication between diverse perspectives, and a tool for crafting strategic planning. The latter – the planning function of foresight – was partially addressed by generating a wide set of plausible risks, and governance mechanisms judged by participants to have the capacity and legitimacy to meet them. I believe, however, that the true success of this exercise was as a communication platform. It highlighted the capacities of deliberation and anticipatory thinking – creating a space for invested thought entrepreneurs to reflect on how governance design depends on imagining risk, and risk depends on not only expertise but bias. Here, I highlight a movement in engagement approach between the final two chapters. The previous study – *Is Bioenergy Carbon Capture and Storage Feasible?* (5) – relied on iterative interviews. This approach allowed for in-depth and personalized interrogations of grounding beliefs and choices, but could not facilitate open deliberation. *Engineering Imaginaries* (6) relied on small-n deliberation, in which structural beliefs posed a starting point for conversations that became swiftly scrambled in generating shared insights on risk and governance.

Chapter 2

Tools of the Trade: Practices and politics of researching the future in climate engineering

Making sense of the implications of climate engineering approaches (solar radiation management, SRM; and carbon dioxide removal, CDR) at planetary scales occurs via a host of methods that calculate, project, and imagine the future in distinct ways. We take a systemic and synthesizing view of some of the (inter)disciplinary methods by which these futures are derived: climate and integrated assessment modeling, 'deductive' modes of social science inquiry, deliberative stakeholder engagement, and foresight-based scenarios. We speak to the epistemologies, objectives, and user communities surrounding these research practices, highlighting that different modes of constructing and interpreting evidence about unformed futures yield different kinds of results and signals for actions to be taken. We show how different methods for exploring 'futures' form an evolving history of how the risks of climate engineering approaches have been assessed (or constructed), and conclude by echoing calls for a stronger shared understanding of the practices and politics that underpin future-oriented research.

Published as: Low, S. and Schäfer, S. (2019). Tools of the Trade: Practices and politics of researching the future in climate engineering. *Sustainability Science*, DOI: 10.1007/s11625-019-00692-x

- Low: Conceptualization; data curation; formal analysis; writing-original draft; writing-review and editing.
- Schäfer: Writing-review and editing

2.1 Future-based evidence making

In the governance of climate change, understandings and decisions in the present are often informed by evidence that speaks of the future. Engineering planetary sunshades (solar radiation management, SRM) or carbon sinks (carbon dioxide removal, CDR; or of late, negative emissions technologies, NETs) are the latest entrants to the landscape of proposals for increasing humanity's capacity to cope with the effects of climate change. These approaches are often described as backed by proofs-of-concept, co-optable from components of existing systems, and sufficiently viable at small scales to merit discussion. They are, however, also often described as 'immature'—not (yet) existing as operational systems, and lacking technical and societal support. Advocacy and opposition thus has in the last decade been shaped by calculations, projections, and imaginings that richly depict the potential benefits and risks of these so-called forms of 'climate engineering' (CE). In doing so, such depictions frame the viability and desirability of different approaches.

We take as axiomatic that 'futures' are politically active resources. Insights into the shaping influences of conceptions of the future can be found in a rich literature on the sociologies of expectations (Borup et al., 2006), sociotechnical imaginaries (Jasanoff & Kim, 2015), or visions (Grin & Grunwald, 2000)—generally in science and technology debates, but also as these intersect with systemic governance issues such as security, health, and the global environment (Granjou et al., 2017). The objective of this contribution is to take a systemic and synthesizing view of the (inter)disciplinary methods by which futures are derived in the discourse on climate engineering. We do so as a point of entry for better understanding how futures are mobilized by scientific practice in an increasingly significant area of climate and sustainability politics. In speaking of methods, we highlight communities of practice, shared objectives and norms, epistemologies for generating evidence, and relative statuses of authority in the ecosystem of climate science and policy. A focus on methods also gives us an entry point into understanding how specific concerns emerge in relation to CE—that is, how different methods cast CE in their image by viewing it as a problem of, for example, changes in temperature and precipitation, interstate conflict and cooperation, the balancing of costs and benefits, or public support or rejection.

Why does this matter? In a field where much attention is directed to imaginary technologies and scenarios of usage, diverse disciplinary understandings inform how such objects are marshaled as evidence. But how does a method of evidence production shape the evidence it produces, or implicitly favor certain perspectives or actors? Our intent is to explore how different ways of making the future known shape the knowledge base upon which climate governance depends. For when particular 'futures' gain a hold on the imagination of scientists, politicians and publics, they can come to structure expectations about what constitutes feasible and desirable courses of action, and shade from view or entirely foreclose alternative options.

We take a bird's eye view of climate and integrated assessment modeling, 'deductive' modes of social science inquiry, deliberative stakeholder engagement, and foresight-based scenarios. The reader will note that methods overlap, complement, or are set in contrast to certain others. Before beginning our overview (section 2.3), we therefore also introduce a number of dimensions for illuminating relationships and contestations between methods (section 2.2, following). Section 2.4 concludes with an attempt to synthesize the links and comparisons established in the overview, showing how our analysis of different methods can be read as a history of how the risks of CE have been assessed (or constructed)—and therefore, how the bounds of the debate itself have come to be configured.

2.2 Some dimensions of future mapping

In this section, we lay out some characteristics by which we can differentiate methods engaged in mapping the concerns and challenges associated with engineering the climate—section 2.3, on the methods themselves, should be read in this light. Needless to say, our list of dimensions is neither exhaustive nor definitive – we derive them from an analysis of relevant literature, from long-standing participation in CE debates, and from an analytical sensibility based in Science and Technology Studies (STS). Like the methods we discuss in section 2.3, these dimensions are geared toward a purpose; in our case, to allow for some systematic conclusions to be drawn about the mutual influences—and tensions—between modes of future-oriented research in CE, and about the overall direction of that work.

The first differentiates between the processes of *quantitative* modeling approaches in natural and social science, and *qualitative* assessments generally deployed as part of social science scholarship. Modeling approaches use simulations based on advanced numeracy. These are simplified representations of reality extrapolated from an understanding of systemic laws (underpinning processes and trends, incentives and constraints) marshaled by quantitative variables and formulae, and that can be computed and aggregated in high numbers of scenarios (of a future moment) or pathways (leading to a future moment)- see section 2.3.1. The others are mixed-methods constructions (scenarios, frames, narratives) that, apart from eschewing a reliance on numeracy, defy easy coherence. Some display a similar logic to simulations, producing scenarios that extrapolate outcomes from systemic processes (2.3.2). Others rely on stakeholder engagements, and on the proposed value of including a diverse range of disciplinary and political perspectives, for exploring challenges (2.3.3).

The second is on the kind of challenges that a method is deployed to investigate surrounding the development or deployment of CE techniques. The dimensions of such inquiry can be (combinations of the) *physical, techno-economic, and socio-political*. Exploration of these challenges is often phrased as assessing 'benefits and risks', though a host of near-synonyms abound. Another way of thinking about it, however, is that methods (and by extension, the communities deploying them, for a variety of agendas and disciplinary understandings) will privilege certain criteria over others in defining risk. We might however also consider if, in the grand scheme of the CE research ecosystem, certain dimensions—that is, some mental and methodological ways of projecting risk—are made subordinate and subsequent to others.

The third parses the process of engaging with futures as *deductive* or *deliberative*. Deduction is a pervasive form of reasoning, where conclusions are reached 'downward' from a set of general assumptions rather than built 'upward' from particular instances. Disciplines across the humanities and the natural sciences provide much nuance on the definition and procedures of this concept. We ask the reader to indulge in a broad definition: if the laws of a system hold—say, the global climate system, or a system of (international) structures and actors, or some analogy of technological development—then if A happens, the analyst, with degrees of likelihood, can expect B, C, or D to result (or can, depending on her mental or computing capacity, trace a sequence of further assumptions and probabilities). From there a conversation opens up on the value of and motivations behind extrapolative, simulative, and probabilistic modes of thought. In the CE space, this includes efforts to gauge climatic as well as societal dimensions of CE; quantitative modeling and more qualitative methods; and disciplines ranging from climate science to economic and sociopolitical inquiry (2.3.1-2.3.2).

A process set in opposition to 'deductive' thinking might be labeled as 'deliberative'—though this term (like deduction) is shorthand for other adjoining concepts. Attempts to cohere such a mode of investigation can particularly be found in frameworks of emerging technology governance that highlight deliberative stakeholder engagement as part of the concept of 'anticipation' (2.3.3). The idea is that thinking about the future as part of a deductive paradigm can be prone to technocracy—there is an implicit emphasis on usable, technically-focused projections, more so than on the processes, values, actors and agendas constructing them. The emphasis, then, should be less on what the 'future' might be (however conditional), and more on who is in the room to say so. 'Futures' should be more explicitly treated as experimental, user-generated, and as inclusive as possible, highlighting the disciplinary and political understandings that create them, and generating avenues for action that navigate a wide array of aims and possibilities.

2.3 Methods of future-oriented research

2.3.1 Climate models and integrated assessment models

The Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) rely upon 'a vast machine' of computer models to simulate future climates—that is, they provide a legitimized mode for forming evidence on the risks of a warming planet, as well as for assessing the viability of strategies to reduce emissions (Edwards, 2010). When 'climate change' emerged as a subject of scientific inquiry—and later, political ambition—an evolving array of model types became entrenched as the principle apparatus by which sense could be made of such a complex, systemic phenomenon. The importance of computer modeling, and the epistemology it represents, is held in place by continued advances in capacity, application to new issues, and mutual reliance between climatic projections and policy discussions.

Deriving the potentials of various CE proposals borrows heavily from the resources and historic credibility of the modelling enterprise. Climate models—underpinning the work of IPCC Working Group I on the physical science of climate change—have been used to estimate the climatic impacts of sunlight reflection methods (SRM). Integrated assessment models (IAMs)—assemblages that combine climate, land-use, energy systems, and economic components—are the vehicles of Working Group III assessments of mitigation options. These have been implicated in the conceptualizing of large-scale carbon removal (CDR) as an essential part of strategies for reaching the Paris Agreement's 2C target. Climate models and IAMs have different histories and applications in the CE space, but we address them together here because of epistemological overlaps in exploring the future.

Climate models were not originally intended to simulate targeted modifications of planetary reflectivity, but have been repurposed for gauging SRM's physical impacts (Wiertz, 2015). This modelling activity has since generated one of the CE debate's largest bodies of literature and authorship networks, relying heavily on the

Geoengineering Model Intercomparison Project, or GeoMIP. Since 2011, research has become increasingly fine-tuned in terms of technology, regions, and impacts assessed (Kravitz et al. 2015). The principle of SRM modelling is straightforwardly deductive. Modellers adjust the reflectivity of various environmental systems as proxies for SRM approaches, resulting in projections of climate variables such as temperature, precipitation, sea level rise, and ozone. Calls for expanding modelling of devolved impacts on agriculture, fisheries, air pollution, and health are increasing (Irvine et al., 2016).

In the climate modelling literature, cooling the planet is broadly projected to reduce certain impacts associated with rising temperatures (Irvine et al., 2016). At the same time, significant variations and uncertainties—particularly on regional effects—depend on assumptions and choices made by researchers themselves. At the input stage, results are structured by the model used, and by the technology, amount, rate, term and location of deployment selected. Any modeller admits to this, but the details of these choices, spread over dozens of papers, are unfortunately if understandably elided. At the output stage, the reporting on benefits and risks, or the very translation work that makes results meaningful for further research or for societal deliberation, often then depends on the communicators in question, be they modellers or others. For example, Irvine et al. (2016) give a technical overview of SRM modelling that also functions as an optimistic prospectus, while McLaren (2018) provides a critical sociological and ethical interrogation.

IAM work on CDR, meanwhile, was not brought into conversations on CE until it was pointed out in the prelude to the negotiation of the Paris Agreement that the vast majority of Working Group III scenarios limiting temperature increases to 2C in 2100 relied on the rapid, large-scale deployment of bioenergy carbon capture and storage (BECCS), an unproven chimera then on the fringes of CDR conversations. The presence of BECCS in resonant AR5 projections, it was argued, provides a 'silver bullet' that scientifically legitimizes ambitious temperature targets as 'feasible', and introduces strange new signals to climate governance. There are concerns over the risks of deploying BECCS, such as land-use conflicts, carbon storage safety, or de-incentivizing emissions reductions, alongside fears that if there few other envisioned paths capable of meeting 2C, then climate policy is being shoehorned into a future generated from these projections (e.g. Beck & Mahony, 2018).

Interestingly, critical commentary also placed an ongoing focus on the role of the research groups built around IAM work as future-makers, resembling points made on the shaping choices of researchers in SRM modeling. The IAM community, it was argued, needs to be aware that their work does not neutrally assess options as much as actively frame their viability and necessity. More uncomfortably, modelers are argued to be complicit in a mode of IPCC assessment in which policy actors invested in the 2C target as a political benchmark functionally trade funding to IAM groups in return for evidence that sustains its viability (Geden & Beck, 2014; Geden, 2016; Anderson, 2015). This, then, calls the impartiality of certain strands of research into question. These issues are further complicated by the fact that contestations over influential technical parameters occur largely within hidden modeling processes, and are often lost in translation during the creation of outputs for wider deliberation (Pindyck, 2017). The IAM community disputes these characterizations, noting that they had consistently warned about over-relying on BECCS and submitted agendas for further research, before rather than in response to critical attention (Tavoni & Socolow, 2013; Fuss et al., 2014). Moreover, they resist the depiction of BECCS as somehow fabricated for filling the gap between reality and climate ambition, arguing that IAMs do not advocate for particular climate strategies as much as simulate emissions pathways with alternative mixes of technology as a platform for policy discussions.

Modelers in either field argue that their work offers fact-grounded but experimental estimates of the future that imperfectly aggregate trends across complex physical and economic systems. The process emphasizes expert judgment as well as 'inter-comparisons' (e.g. GeoMIP for SRM) where a comparison between a range of models aiming at common targets is argued to contextualise outliers and deliver conclusions with greater confidence. In this understanding, knowledge of climatic impacts of CE approaches, or of barriers to deploying them, can be produced or improved by refining inputs or by running a greater diversity of scenarios. Stronger modelling capacity and further modelling applications are seen to improve understanding of certain dimensions of risk, and their simplified, often intentionally limited parameters have to be taken into account when applying modeling results to policy crafting.

These are fair conditions, but their limitations are worth considering. Climate models, for example, have been argued to be an 'inventive tool' in the design of SRM strategies, in which planetary sunshades are 'virtual technologies' constructed and framed strongly within the bounds allowed by modelling capacity (Wiertz, 2015). They are also black boxes imbued with the credibility of the modelling enterprise, from which conflicting choices and results can be selectively emphasized. More critical scholarship notes that this combination of expert judgment and complex model structure allows for much freedom in shaping the bounds—and results—of modelling scenarios. But choices contested within modelling communities require a high bar of basic literacy, translate poorly to non-specialist audiences, and may even distract from political agendas or biases that remain less investigated or revealed (e.g., Wiertz, 2015 and McLaren, 2018 for SRM; Beck & Mahony, 2018 for BECCS). Criticisms of technocracy can hardly be limited to modellers; critics also do not deny the value of modelling work in certain domains. That said, there is a difference in emphasis on the role of the researcher. Critical scholarship, more so than modeling papers, emphasizes the political dimensions of research practice where results may appear more as artifacts of the methods that form modeling practice and the myriad agendas and pressures surrounding climate science.

This focus on the construction of evidence through research practice is helpful when considering that modeling activity in the CE space explores a deliberately limited set of dimensions. SRM modelers note that the risks they assess are limited to climatic processes and impacts. Integrated assessment modelers are frank that BECCS-heavy scenarios in AR5 were calculated based on technical, economically efficient criteria for scaling up infrastructure, and deliberately bracket sociopolitical dimensions. Yet, both therefore contain bracketed conceptualizations—of 'risk' for SRM, or 'feasibility' for BECCS—that functionally emphasize the physical or techno-economic criteria that modeling infrastructure is able to portray, ahead of the societal dimensions of deployment. Such politically and historically 'thin' scenarios do not capture historic culpability, vulnerability, need, and capacity; as such, they demand solutions divorced from the context in which the snapshot emerged (McLaren, 2018). For example, the scaling up of BECCS, in many AR5 scenarios commencing heavily during the 2030s, assumes facilitating conditions on a global level and elides inequities in technological capacity and (carbon) geopolitics. This would be a deceptive basis upon which to build a case for BECCS, given resilient controversies surrounding the production of biomass for energy, or carbon capture and storage.

There is a further concern that scenarios can signal the need for politics to catch up to, or strongly avoid, the modelled reality. This is complicated by ambiguities surrounding the intents of modelling for explicitly providing decision-making support. IAM work—more established as a science-for-policy enterprise than SRM modeling due to its role in WGIII work in the IPCC process—tends to frame itself as neutral 'map-making', following the 'policy relevant but not policy prescriptive' ethos of the IPCC (Edenhofer & Minx, 2014); the signaling implications of their 'maps' for expectations in climate governance, however, are highlighted in Beck and Mahony (2018). By contrast, SRM modeling networks have no common platform. GeoMIP's earlier efforts were geared more to model validation than policy; bluntly designed to induce strong impacts in the earth system in order to garner broad understandings of engineered climates, rather than reflect what might be climatically or politically 'desirable' (however this is to be defined). Some modellers have more recently argued that scenarios assuming stronger mitigation and moderate SRM provide more tempered and realistic results for policy deliberation (Keith & MacMartin, 2015). But are the conclusions of idealised studies deployed in political settings in a manner that exceeds their mandate? If so, what are the responsibilities of those involved—generators (e.g. modellers), translators (expert networks in climate governance), and audiences (civic and policy communities)?

Tensions between the purposes of modelling for improving systems understandings, calibrating modelling practice, or providing a workable basis for informing climate policy; or alternately, between the grounding of modelling outputs in real world processes and their extrapolation into more fantastic possibilities, remain unresolved dimensions of this mode of research. But that modelling has both value and limitations in structure and application is not in dispute, neither by its practitioners nor by adjoining networks of (critical) experts. In what follows, we explore whether there is some disproportionate importance given to the epistemologies and practices of futures assessment represented by modelling in the CE research ecosystem, whether there are efforts to change these logics in research practice, and if these efforts can fruitfully co-exist.

2.3.2 Deductive reasoning in socio-political inquiry

While integrated assessment models do represent the social world in certain constrained ways, we now enter an area in which the focus is placed squarely on 'the social.' No method for exploring the sociopolitical dimensions of CE approaches is as dominant as modeling is regarding climatic effects. In approaching those dimensions, however, the methodologies examined here are in some ways epistemologically similar to the logics underpinning computer simulations: again, what we refer to as a 'deductive' approach. Expanded into social inquiry, dynamics are deduced from an initial set of starting conditions following the logic of the given methodology, assuming some set of stable covering laws; this is a common but contested approach across economics, political science, and international relations. The latter pair of disciplines has imported key assumptions, and even statistical and modeling approaches, from economics (where influences have been traced further back to attempts at modeling social inquiry after the principles of physics) in the guises of rational choice theory and its offshoots (Bernstein et al., 2000). Through the application of those approaches, deductive thinking is a general presence in discussions of the 'social impacts' that CE approaches, as well as other fields of emerging sociotechnical systems, may have, despite criticism of such thinking from social scientific and humanist disciplines such as science and technology studies (e.g., Bijker et al., 1987).

One prominent vein is interested in the international political dynamics around SRM, forming a body of game-theoretic modeling studies that simulate the strategic actions of states regarding the development or deployment of SRM (Harding and Moreno-Cruz 2016), with implications for some outcome of interest to the study: for example, the formation of coalitions of SRM-capable states in Ricke et al. (2013), environmental treaty formation in Millard-Ball (2012), or emission reductions in Urpelainen (2012). These calculations unfold according to some set of covering laws: Notably, states are represented as rational, strategic and unitary maximizers of benefits and minimizers of costs, following the concept of a 'homo oeconomicus' imported from microeconomic theory. Often, knowledge on the physical impacts of SRM deployments generated via climate modeling efforts discussed in section 3.1 serves as input for informing state preferences.

By giving a 'parsimonious' account of international political dynamics, such exercises can explain and, by extension, project outcomes with some predictive capacity precisely because of their high level of abstraction—or so proponents argue. Summarizing conclusions are difficult to reach due to differing aims: Urpelainen (2012) and Millard Ball (2012) point out consequences of unilateral SRM on mitigation efforts; Ricke et al. (2013) conclude that a small-as-possible club of first-moving states will have an incentive to exclude new members that might upset their established preferences. To non-specialists, such exercises can appear based on highly simplified assumptions, and removed from the concerns that more qualitatively oriented scholarship takes to be at work in international politics. These dynamics of justification and critique can be observed regarding other modeling and simulative activities—for example, on the emergence of BECCS as a strategy for mitigation in integrated assessment modeling scenarios (3.1).

Unlike the use of climate and integrated assessment models, a critical summary and interrogation of this body of modeling work has yet to be undertaken—for its epistemology, actors, and its unfolding implications in CE research. Some critiques would likely be imported (and contested by economic modelers): Abstracting complex societal trends and dynamics via numeracy (however advanced); the eliding of influential choices on modeling parameters made by researchers (however unintentionally); the relevance of politically 'thin' work that results from simplifying context, time, and value-specific concerns (however necessarily for calculability and parsimony). Whether or not these game theoretic studies present potentials for building momentum behind realities they represent is another matter (e.g. BECCS in climate discussions); they do not appear to have had significant traction beyond internal debates in CE research networks. It is, perhaps, a space to watch.

Deductive reasoning is also found in less formalized analyses (as opposed to the highly formalized nature of game theory) regarding the politics of CE deployment, generally grouped within international relations or political science literatures. Neither discipline professes to be in the business of prediction; yet it is quite common to establish systemic understandings of the driving motivations and dynamics of (international) politics that can then be presumed to shape actions and effects. What binds these otherwise disparate studies together is the understanding that future (interstate) dynamics can be extrapolated from the assumption that SRM or CDR will grow up in a world embodied by particular problem structures—some understanding of the international system, some logic of conflict potential, some knowledge about environmental or technological consequences—that hold true for mapping its future politics.

For example, Horton and Reynolds (2016) call for studies utilizing leading international relations theories (e.g. realism, institutionalism, liberalism, and constructivism) to help structure thinking on the potential intersections between CE deployment, mitigation efforts, conflict, North-South relations, and governance challenges. Many security studies similarly rely on a systematic understanding of the motivations and constraints facing international actors to deduce implications for conflict over CE, implying that deployment would follow existing logics of 'potentials for direct conflict' like resource scarcity (Maas & Scheffran 2012), or that the promise of doing it would breed systemic brinksmanship in climate politics (the 'security hazard', Corry, 2017). Studies can rely implicitly upon knowledge about environmental and technical consequences or 'side effects' to deduce political implications. Indeed, it is often the supposed environmental impacts that get first mention: for example, for SRM, changing temperature and precipitation patterns. For some, this sequencing is explicitly desirable, lest, to paraphrase Victor et al. (2013), the politics of geoengineering get far ahead of the science. This has similarly often been the case for assessments of governance and policy options; early governance proposals tended to emphasize management of physical risks, and 'tailor the amount of scrutiny to the scale' thereof (Lin, 2016, p. 2538).

That environmental and climatic consequences of human activity have political knock-ons, and that systemic structures shape distributed outcomes, is seldomly contested in principle. Disagreement with these assumptions is based more on the priority thought to be given to technical and physical criteria of risk, or a perceived disposition of deductive social inquiry to expert-driven narratives and technocratic research, than on the notion that they are wrong in principle. In section 2.3.3, we trace pushback emerging against research practices that facilitate these modes of thinking.

2.3.3 Deliberative stakeholder engagement and foresight approaches

If the works of the previous section represent a 'deductive' mode of social science, then a burgeoning field of 'empirical' social science (Burns et al. 2016) posits that understandings of concerns and values regarding future risks and challenges can be sourced from engagements with scientific, policy, and civic stakeholders. From there, however, procedures and intents underpinning engagement work diverge. A network of (largely) UK-based scholars and practitioners highlight that two distinct 'waves' of stakeholder engagements can be observed. In the first wave, it was argued, procedures were functionally entrenching SRM and CDR approaches as 'policy objects' (the accused include e.g., Ipsos MORI, 2010; Mercer et al., 2011). Questions were asked, and discussion configured, around technical dimensions and thresholds of effectiveness, safety and cost that purportedly made CE approaches more researchable or actionable for the projected desires of 'policy-makers', disaggregated into individual technologies for 'differentiated governance', and with increased examination of stages of research or 'reduction of uncertainties' rather than broader social and ethical questions (Corner et al., 2013; Owen, 2014).

Engagements of a so-called 'Second Wave' would utilize deliberative exercises—described generally as innovative dialogues highlighting different perspectives in exploring futures, with minimal prefacing work by experts. This would ideally create a space for discussing CE's means and ends in an open-ended, substantive manner, while 'un-framing' them as policy objects (for a summary of such exercises, see Bellamy & Lezaun, 2017). Significantly, this body of work invoked the principles of 'anticipatory governance' (Guston, 2014), and 'responsible research and innovation (RRI)' (Stilgoe et al., 2013)— deliberative and future-oriented frameworks for the governance of emerging technologies. Both had previously seen concerted application in nanotechnology debates, and can be seen as an importation, by its practitioners, of an evolving toolkit of governance concepts and research practices from one realm of emerging techno-science into another (for a history of this 'amalgam of ideas', see Burget et al., 2017).

Methodologically, advocates of these frameworks contend that the current paradigm in future-oriented research places an undue focus on 'outcomes' rather than 'processes': that is, on the accuracy and usability of future projections of technology for policy, rather than on the epistemologies and choices on which these are pieced together; and on public engagement as a kind of reporting mechanism for audiences after-the-fact, rather than a deliberative activity from the outset that helps inform the objectives of scientific work. The argument is that this paradigm privileges and elides the role of 'key enactors' in setting and framing risks, reserving capacity to frame the boundaries of the debate for particularly invested constituencies while simultaneously portraying this process as apolitical (Owen, 2014). Substantively, RRI practitioners in the CE space set themselves up against a reliance on technical knowledge as a baseline for defining societal challenges, or framing CE approaches as a narrow response to climate change rather than game-changing endeavors in their own right (Bellamy & Lezaun, 2017; Foley et al., 2018).

One can admire the mission statement of RRI while interrogating its execution. Some have observed that the publications of this 'Second Wave' of engagements produce conclusions that counter-frame the viability and desirability of CE approaches as successfully as the framers they seek to counteract (Heyward & Rayner 2013). Bellamy et al. (2013), as a typical example of 'Second Wave' work, concludes that when engagements focus on more expansive societal concerns rather than on technical questions of cost and efficiency, participants tend to de-prioritise CE approaches. Macnaghten and Szerszynski (2013) more forcefully point to the 'centralising and autocratic social constitution' of sunlight reflection methods, and question if it is compatible with democratic governance. Heyward and Rayner (2013) argue Macnaghten and Szerszynski's conclusions reflect a 'curious asymmetry', in which these characterizations are applied to forms of CE, yet not uniformly so to a variety of other governance proposals with similarly global, centralizing implications. The implication is that some RRI practitioners in this space, in seeking to 'unframe' climate engineering and retard its lock-in as a set of policy options, can be quieter on their own framing choices.

There is a larger point to be made, however obvious. RRI is not just a procedural framework for bettering participation; it is an umbrella concept for sets of political activities, representing the agendas and logics of particular networks in specific areas of emerging technology assessment, as well as particular conceptions of the proper relationship between science and society. The political may influence how the procedural is developed and executed, and to focus on the procedural alone de-politicises RRI as a concept and its practitioners as actors (see Van Oudheusden, 2014). Engagements and critiques invoking RRI in the CE space focus more on interrogating the actors and signaling effects of modes of inquiry deemed to operationalize CE approaches (e.g. prioritizing technical metrics over societal and normative questions) or elide the shaping influences of researchers (e.g. in modeling), than its own practice and politics. One need not devalue their work while asking the question of who is watching the watchers.

An adjacent corner of this ad-hoc field of deliberative methods requires its own mention, due to nuances in history and application. ‘Foresight’ approaches have recently found a limited traction in the CE space: predominantly (though not exclusively) as ‘explorative’ scenario-building exercises, and increasingly (though not initially) under the rubric of anticipatory frameworks. Long practiced as a set of prognostic and planning tools in military and business settings, foresight struggled for acceptance in the social sciences in earlier guises as ‘futurology’ or ‘future studies’. However, overlaps were established between foresight practice and scholarship examining the shaping effects of claims to the future in emerging techno-science fields, and incorporated as a principal component of ‘anticipatory governance’ ('Foresight' in Guston, 2014) and later in RRI ('Anticipation' in Stilgoe et al., 2013). Both frameworks invoke the use of scenario work—emphasizing its potential to enhance deliberation and critical reflection amongst participants—to map future-making processes.

Scenarios, in this understanding, reject probabilistic forecasting in favor of small sets of futures that are rich in sociopolitical detail, highly differentiated (or ‘alternative’) and easily comparable, and are developed deliberatively between diverse viewpoints. Scenarios are in turn supposed to be experimental: provoking reflection by participants on specific conceptions of future threats and opportunities, on why these conceptions (but not others) made the cut, and on strategies that might be resilient against or adaptable to a wide variety of possible outcomes rather than tailored to a more limited set of predictions (Vervoort & Gupta, 2018). Most exercises in the CE space were developed in expert-driven workshops with small participation numbers, developing ‘explorative’ scenarios that reflect on the challenges presented to—and by—efforts to govern SRM or CDR development under a variety of environmental and societal pressures (Low, 2017b). We might note that early CE scenarios were motivated by older principles of foresight rather than by RRI. Alongside deliberative engagement exercises, scenario work began to invoke RRI as that framework became popularized (Low, 2017a; Bellamy & Healey, 2018).

Whether conducted under the spirit or the letter of RRI, foresight’s practitioners pose it as a corrective logic to inertial modes of inquiry that lend greater credence to evidence grounded in hindsight, and portray researchers as aloof from rather than constitutive of the ‘futures’ they assess. Both are points of view antithetical to the practice-oriented prospection that foresight represents (Selin, 2008). The framing effects of this small collection of exercises on the wider debate, however, are for now minimal. For a start, the field suffers from low visibility, and has not generated resonant conclusions on risk or governance that one might examine for motive and effect. Scenarios sometimes turn out too outlandishly to be actionable or recombine risks already derived in other studies. Moreover, its objectives and conclusions are internally incoherent. Practitioners are divided on the use of foresight for creating 'actionable' knowledge for strategic framing and policy guidance, or for communicating between and interrogating participating perspectives as part of 'community learning' (Talberg et al., 2018; Gabriel & Low, 2018). However, as a deliberative tool, foresight shares much with (and is often used for) stakeholder engagement – this is where it may currently hold more credibility in the CE space. As with engagement exercises conducted under the RRI banner, one can question if foresight applications fulfill ambitions of 'opening up' the debate to more plural processes, or produce results with veiled political and normative commitments.

2.4 A shared understanding of 'futures' research

Our intent here has been to question if research methods produce assumptions that structure how 'futures' are generated and acted upon in the present. What are the kinds of risk highlighted by those futures, and positioned as relevant concerns for research and policy in the present? What are epistemologies, expertises, and agendas that they come tied up with, and what actors do they privilege? In short: How do methods and their users configure the bounds of the debate? From the above analysis, we distil some underlying currents in the construction of climate engineering futures. What follows is not intended as definitive, or as a strict dichotomy; however, we believe that it captures relevant differences in broad strokes.

First, the dimensions represented by modelling—the capacity of numeracy to capture and simulate complex dynamics, the functional focus on physical and techno-economic aspects, characterizations as science 'proper'—often occupy a position of epistemological primacy. We can consider, for example, the expansion of modeling logics into assessments that focus upon political and societal questions, or (more tenuously) the resilience of deductive reasoning across research practice. Moreover, and with particular relevance to SRM, socio-political assessments—in game theory, deductive inquiry into risk, even some engagement work—position politics as efforts to navigate the 'climates' generated by physical science modelling.

This is not to write off the usefulness of such simulations. These can yield imperfect but valuable observations about the environmental or technical dimensions that they are designed to explore; indeed, one can reasonably argue that different epistemologies and practices of assessment tackle different areas of the puzzle. Models, one might note, cannot determine public values any more than deliberative engagement can determine the physical science of precipitation; the challenge is for the results of different areas of investigation to fruitfully inform each other. Yet, this proposed division of labour might be a little simplistic: All research practices (and users) are already engaged in a larger system where judgment is passed, in ways that defy simple boundary-drawing between methods and expert communities, on the viability and desirability of kinds of CE. Plainly put: the use of research often exceeds the bounds of its design.

The question critics (and the authors as well) raise is whether limited conceptions and calculations of risk, and the 'futures' they frame, are inertially and disproportionately prominent within CE's research ecosystem because they are more amenable to modelling practices. This is seen to be amplified by other perceived factors: If modelling, as a mode of futures-exploration, retains a particular, historic resonance and credibility in climate science and governance; if the CE research enterprise is, as is the case for much work in emerging fields of science and technology, characterized strongly by the expectation to create actionable, or policy relevant evidence; and if expert-driven assessment, however unintentionally, often leans toward technocracy. In partial response to these concerns (within and outside of CE), more deliberative practices of social inquiry—increasingly marshalled under the banner of RRI or 'anticipatory' assessment of immature technological systems—have developed a growing presence. These attempt to present alternatives by repositioning politics as constitutive of, and not subordinate to, science. Deliberative engagement, at least in mission statement, presents an increasing variety of civic and policy audiences with the opportunity to frame the implications of engineered climates on their own terms. But although posing corrective measures to technical and technocratic future-making, some actors in this space have been critiqued as bringing with them their own normative commitments regarding the desirability of the climate engineering enterprise. The observation, then, that research practice is political is not applicable only to modeling work. Approaches for bettering process such as RRI need to be examined as tied to the forms of expertise, agendas, and blind spots of its practitioners, as much as the activities that they interrogate.

All this is to point out that practitioners in this space can and should work to enhance complementarity between methods and users—not simply by 'putting them in their place', or allowing different methods to assess different questions—but by also building a shared understanding of the practices and politics that underpin future-oriented research. This, ideally, might allow for more fluid, mutual access between disciplinary communities, or with stakeholders from a variety of demographics and polities, in shaping objectives and methods of research. Efforts across disciplines to clarify the intents and limits of various methods remain low hanging fruits, as is deepening the interdisciplinarity of research projects (for a critique of the imperfect degree of mutual learning in assessments, see Foley et al., 2018). Understanding 'boundary work' is especially useful for cross-disciplinary learning: the idea that concepts ostensibly common to different expert, civic, or policy communities—for example, 'deductive' and 'deliberative', 'risk' and 'feasibility', 'expert judgment', 'scenarios', 'futures', and even 'sustainability'—are likely understood and practiced with tribal nuances and agendas (e.g. Shackley & Wynne 1996).

Illustrations of research practice with a stronger blending of disciplines might also be helpful. Much foresight work in this space, for example, combines discussion of climatic, societal, and political trends to build 'futures' that reflect the forms of expertise and concerns of diverse participants—a combination of deliberative engagement with elements of simulative work for a more participatory kind of scenario construction. Also of interest to the authors are proposals to integrate principles of 'deliberation' and 'anticipation' (again, research generated jointly between experts and publics, that highlights rather than elides non-technical perspectives) into climatic, game theoretic, or integrated assessment modelling—precisely the kind of knowledge production where a high bar for literacy creates a high barrier to entry. Greater attention thus needs to be paid not just to the outcomes of analyses—what the benefits and risks of future technologies supposedly are—but to the methodological processes through which such knowledge is produced, to how these processes structure our knowledge in ways that illuminate certain benefits and risks over others, and to the building of shared epistemologies and practices that explore different 'futures' of climate, society, and sustainability in reflexive and experimental ways.

Chapter 3

The Practice of Responsible Research and Innovation in 'Climate Engineering'

Sunlight reflection and carbon removal proposals for 'climate engineering' (CE) confront governance challenges that many emerging technologies face: their futures are uncertain, and by the time one can discern their shape or impacts, vested interests may block regulation, and publics are often left out of decision-making about them. In response to these challenges, 'Responsible Research and Innovation' (RRI) has emerged as a framework to critique and correct for technocratic governance of emerging technologies, and CE has emerged as a prime case of where it can be helpfully applied. However, a critical lens is rarely applied to RRI itself. In this review, we first survey how RRI thinking has already been applied to both carbon removal and sunlight reflection methods for climate intervention. We examine how RRI is employed in four types of activities: assessment processes and reports, principles and protocols for research governance, critical mappings of research, and deliberative and futuring engagements. Drawing upon this review, we identify tensions in RRI practice, including whether RRI forms or informs choices, the positionalities of RRI practitioners, and ways in which RRI activities enable or disable particular climate interventions. Finally, we recommend that RRI should situate CE within the long arc of sociotechnical proposals for addressing climate change, more actively connect interrogations of the knowledge economy with reparative engagements, include local or actor-specific contexts, design authoritative assessments grounded in RRI, and go beyond treating critique and engagement as 'de facto' governance.

Published as: Low, S. and Buck, H.J. (2020). The Practice of Responsible Research and Innovation in 'Climate Engineering'. *WIREs Climate Change* 644. DOI: 10.1002/wcc.644

- Low: Conceptualization; data curation; formal analysis; writing-original draft; writing-review and editing.
- Buck: Conceptualization; writing-review and editing.

3.1 Introduction

In March 2019, the Swiss delegation sponsored a resolution at the UN Environment Assembly (UNEA) for the UN Environment Programme to undertake a vaguely-defined assessment process of 'geoengineering and its governance'. In the proposal, geoengineering (we use the synonym 'climate engineering, or CE) encompassed both novel, planetary-scale sunshades (sunlight reflection methods, SRM) and carbon sinks (carbon dioxide removal, CDR; of late, negative emissions, NETs). The resolution's failure was attributable to a number of reasons, including timing, terminology, and the broader implications of assessment for governance (Jinnah & Nicholson, 2019) and was ultimately stymied by US and Saudi Arabia-led efforts to keep discussion of CE under the auspices of the Intergovernmental Panel on Climate Change (IPCC). Under the IPCC, analysis would be constrained to science rather than governance (Economist, 2019).

The failed UNEA proposal reflects challenges around assessing technologies and climate pathways. 'Authoritative assessments' continue to be important for establishing benchmarks in both scientific and political arenas, and have steering effects in future activity (Gupta & Möller, 2018). Struggles are still playing out around the shape and scope of such assessment: when it is appropriate to assess it? By whom it should be assessed? What purpose does assessment serve?

These are central questions for scholars and practitioners informed by 'Responsible Research and Innovation', or RRI—and this includes ourselves. RRI is described by its practitioners as a wide-ranging set of philosophies and procedures for aligning the governance of novel fields of science and technology with societal values (Burget et al., 2017; Ribeiro et al., 2017). Informed by Science, Technology, and Society studies (STS), RRI is concerned with 'governance' as more than risk management through regulatory policy. Rather, RRI sees governance as maintaining a dialogue with society about how a field's envisioned trajectory and risks are constructed, shaped by oft-hidden politics of scientific assessment and technological innovation. RRI seeks to not only generate but incorporate societal concerns into future assessment and regulation. 'Deliberative' conversations, often within 'mini-publics', are seen as an ideal vehicle for developing alternative conceptions of risks that challenge technocratic narratives and pose reparative measures. In principle, RRI can inform governance from the laboratory and research programme to the funding agency and the patent regime. In practice, RRI-informed activity—at least in CE fields— is pragmatically slanted towards academic spheres of critique and engagement.

One can think of RRI as the latest in a range of frameworks—versions of 'Technology Assessment' (Schot & Rip, 1997); 'Post-Normal Science' (Funtowicz & Ravetz, 1993); 'Transdisciplinarity' (Lang et al., 2012)—that have sought to turn longstanding STS insights on the constructed and political nature of scientific knowledge into engaged practice within contemporary scientific and technological governance. There is an element of old wine in new bottles. The term can be seen as a politically-invented attempt to bring together a heterogeneous set of practices and interventions; at the same time, the added value of RRI comes arguably from its mobilization of ideas re-purposed from antecedent frameworks and literatures (Ribeiro et al., 2017). Concurrent with 'Anticipatory Governance' (Guston, 2014), RRI has become popularized in European contexts due in part to strong reference in Horizon 2020, the European Commission's research and innovation programme (de Saille, 2015).

RRI and climate engineering are a mutually-foundational pairing of governance theory and case study—Stilgoe et al. 2013, a resonant prospectus of RRI, is grounded in an episode of SRM research governance. RRI interrogations have argued that the CE research ecosystem has often reflected and reinforced a particular paradigm: technical assessment of costs and risks as 'actionable evidence'; a separate and secondary examination of societal dimensions; and treatment of stakeholder engagement as communication of scientific results. RRI, then, sets itself up broadly as a set of corrective measures to the practice and politics of technocracy. But RRI has not been questioned itself to a similar and corresponding degree. As climate engineering continues to be discussed—and as carbon removal gains interest from companies and policymakers—it is crucial that we understand the present context of RRI with regards to climate responses, including its limitations. This paper reviews how RRI has been employed in CE conversations, identifies tensions embedded in its practice, and make recommendations for future RRI-informed work. In doing so, we intend for the paper to reflect the thing it reviews: a critical examination of science and innovation governance informed by the traditions of STS.

3.2 A review of RRI practice in climate engineering

RRI was first brought into CE conversations in the early 2010s by practitioners who had pioneered its application in US and UK-based nanotechnology initiatives. RRI's initial anchor was the development of an advisory panel and 'stage-gate' process around the testing of a deployment mechanism (a large balloon) in a small-scale SRM outdoor experiment hosted by a university consortium in the UK (the 'test-bed' of the SPICE Project). The SPICE test-bed's travails and eventual cancellation in 2012 serves as the underpinning case study of Stilgoe et al. (2013), which lays out RRI's principles for enacting responsibility in science governance (see also Owen, 2014; Stilgoe, 2015).

In this decade of climate engineering research, we can trace RRI-informed activity in four overlapping areas—noting that 'RRI' is not a unified tribe implicated in the same aims and actions. What constitutes an 'RRI-informed' activity? In straightforward cases, the activity—which could be an intellectual product, a study, a deliberative event, or a line of scholarship—is defined as informed by RRI by the author(s). But often, principles of RRI are implicit in a study's intent and process, and we include such works in our review. We are wary that various works of engagement, discourse analysis, sociology, anthropology, and foresight can thereby be claimed in retrospect as examples of RRI practice, but there is reason to take account of them. RRI, firstly, draws upon these disciplines. And even if studies do not mention RRI as a motivating framework, they may dovetail with its intents; they may cite, and be cited by, RRI studies to reinforce mutually agreeable points.

3.2.1 Assessment processes and reports

The first body of RRI-informed critique addresses the grey literature of assessment reports, exploring how experts setting the terms of debate has framing effects as part of 'de facto governance'—the privileging of particular objectives for assessment, risk dimensions, areas of expertise and epistemology, and avenues for action that serve as informal but resonant conventions for bounding research (e.g. Gupta & Möller, 2018; see also Rip, 2014). Owen (2014), Morrow (2017), Gupta and Möller (2018), and Foley et al. (2019) critique a perceived 'actionable evidence' paradigm in seminal reports, as well as a countering mode of 'responsible' or 'anticipatory' assessment. All four highlight the seminal Royal Society report (Shepherd et al., 2009) as laying out a template followed in most subsequent assessments. The paired National Academies of Science reports on CDR and SRM (McNutt et al., 2015a; McNutt et al., 2015b) are argued to be especially technocratic and physical science-based, and in particular to set in motion a framing of SRM as a security issue at the deployment level, but as an issue of technical assessment at smaller level—this seeks to enable SRM at lower scales in 'allowed zones' (Morrow, 2017; Gupta & Möller, 2018). Assessment, then, should explore societal and ethical concerns via deliberative engagements, rather than place ontological primacy on technical and physical risk via modelling and engineering calculations. It should engage in open-ended questioning, rather than normalize CE approaches via metrics of 'costs' and 'effectiveness' that make it digestible for policy. It should engage society as co-designers of research objectives and process, rather than as mere sources for data or audiences for results. And it should highlight the responsibilities of expert communities in shaping knowledge, rather than transfer responsibility for 'using' that knowledge to society (Owen, 2014; Foley et al., 2018).

Accordingly, some reports, due to participation of RRI-informed scholars, attempt to formulate more deliberative assessment processes and governance recommendations. The Bipartisan Policy Center's report (Long et al., 2010) calls for exploratory foresight, substantive engagement, and collaborative, multidisciplinary approaches arguably due to the presence of 'Anticipatory Governance' practitioners (noted by Foley et al., 2018). The Forum for Climate Engineering Assessment's report on SRM governance was generated by an Academic Working Group of social scientists and policy analysts; the report (Chhetri et al., 2018) emphasized 'responsible knowledge creation' as a core objective, and devoted six of its twelve governance recommendations to concrete ideas for infusing principles and methods associated with RRI practice into existing governance systems at multiple levels.

3.2.2 Principles and protocols

Most RRI-informed activity, however, takes place in the wider research ecosystem, where work is not coordinated as part of a commissioned assessment, but within which authorship networks, frames and received wisdoms, and 'de facto' governance can nevertheless be observed. We begin with what has evolved in later communications as variants of 'principles and protocols' (e.g. Bellamy & Healey, 2018).

The seminal example here is the 'Oxford Principles'. A set of five short research guidelines (regulation as a public good; public participation in decision-making; disclosure of research; independent impacts assessment; governance before deployment) generated in 2009 by a multidisciplinary group of UK-based academics, the Oxford Principles' value has been argued by its creators to be as a 'bottom up and incremental approach' with sufficient room for future activities to fit into, and as such, to be appropriate for an ever-evolving debate (Rayner et al. 2013). The Oxford Principles inspired a wave of such efforts: see the lists of principles contained in Asilomar (2010), Long et al. (2010) and Schäfer et al. (2015).

Informal 'principles' can also be seen in terms of both governance frameworks and guidelines for knowledge production. When it comes to governance, Stilgoe et al. (2013) describes RRI to be informed by 'Anticipation, Reflexivity, Inclusion, and

Responsiveness'; this resembles and is clearly mutually informed by 'Foresight, Engagement, Integration, and Ensemblization', the guiding principles of the concurrent framework of 'Anticipatory Governance' (Barben et al., 2008; Guston, 2014; Foley et al., 2018). Bellamy (2016) draws on both, calling for 'reflexive foresight', judgment of CE based on 'robustness' across multiple worldviews rather than technical optimality, and 'legitimacy' as decided by societal debate. The key takeaway is although a premium is placed on understanding the political economy of futures-making, RRI practice must do more than map context—it must create engagements, reflect upon them, and tie the insights to concrete governance. Scholarship informed by RRI and STS also suggests informal principles for knowledge production, juxtaposing modes of instrumental knowledge production against an arguably more participatory and reflexive mode. These modes are phrased as 'technocratic vs. democratic' (Owen, 2014), as 'deductive' or 'deliberative' activity (Low & Schäfer, 2019), as 'solutionist' against 'experimentalist' research and governance (Asayama et al., 2019), or, resonantly, as a matter of 'opening up' rather than 'closing down' technology appraisal (Stirling, 2008; Chilvers & Kearnes, 2019).

3.2.3 Critical analyses of research

A number of ethnographies or critical examinations of discourse in research practice have applied these principles piecemeal, as part of individual studies (in contrast to a sustained assessment or governance process). Many such studies are not conducted under RRI's banner. However, they perform a kindred function of exposing the substance of arguments and power dynamics in the research landscape. Moreover, they are cited by studies, and provide background context for anchoring deliberative engagements, that explicitly invoke RRI.

A key example of this is the large literature of content mapping and discourse analyses of frames and narratives from media, academia, and policy that assess how CE is packaged and received (Porter & Hulme, 2013; Scholte et al., 2013; Huttunen et al., 2014; Oldham et al., 2014; Harnisch et al., 2015; Linner & Wibeck, 2015; Himmelsbach, 2018). These analyses include maps of moral positionings (Betz & Cacean, 2011); framings of advocacy, detraction, and appropriate governance (Anshelm & Hansson, 2014a; 2014b; Cairns & Stirling, 2014; Boettcher, 2019; Boettcher, 2020); metaphors with medical, mechanistic, and military connotations (Nerlich & Jaspal, 2012; Luokkanen et al., 2013); and kinds of 'catastrophism' (Asayama, 2015).

Later studies explicitly informed by STS explore how scientific 'knowledge' of CE's potentials is constructed, though from a more systemic than specific (e.g. an actor's or institution's) point of view. Low and Schäfer (2019) argue that different modes of research practice (e.g. technical modelling vs. deliberative engagements) emphasize particular types of risk, and entrench the status and biases of actors with relevant expertise. Talberg et al. (2018) examine underpinning assumptions and signaling implications of different kinds of 'scenarios' (both modelling and more qualitative imaginings); Gupta and Möller (2018) explores 'normalizing' frames set in motion by authoritative assessment reports as de facto governance.

This literature strongly interrogates modeling practice. One half of this work focuses on the modelling of SRM deployment schemes and impacts via earth systems models. Wiertz (2015) provides the earliest interrogation in the CE literature of evidence construction and validation within modelling structures; Flegal (2018) is a comprehensive update, with an emphasis on the advocative tendencies of actors who rely on modelling results. Flegal and Gupta (2018) and McLaren (2018) argue that dimensions of (in)equity and (in)justice are set in motion by SRM scenarios, while Schubert (2019) traces how the forceful numeracy of modelling has shaped the discussion of SRM in the US.

The other half unpacks the origins and ongoing implications of 'bio-energy carbon capture and storage' (BECCS) in scenarios calculated by integrated assessment models (IAMs) for the IPCC's Fifth Assessment Report (AR5). BECCS is integral to scenarios that keep temperatures at century's end below 2C; a threshold that would, a year later, be adopted in the Paris Agreement. BECCS, as well as the IAM research community, have since been interrogated for their roles in underpinning otherwise improbable climate targets, with scrutiny given to the normalization of BECCS and carbon budget 'overshoot' in expectations for future climate politics (Beck & Mahony, 2018a; Haikola et al., 2019); the quid pro quos and tensions between IAM work and political imperatives (Geden & Beck, 2014; Beck & Mahony, 2018b); and the history, practices, and perspectives of the IAM community in producing what Jasanoff (2004) calls 'regulatory science' (Guillemot, 2018; Haikola et al., 2019; Cointe et al., 2020; Low & Schäfer, 2020).

3.2.4 Deliberative engagement and futuring

If critical analyses map the knowledge and political economies with an eye to inequities, RRI also generates engagements with those missing constituencies, and develops 'futures' that represent under-investigated discourses and profiles of risk and uncertainty. The objective is to be explicitly 'generative' (Vervoort, 2019), and not simply to recognize the (perverse) signals and effects of existing imaginaries, but to create alternative narratives (Stilgoe et al., 2013; Vervoort & Gupta 2018; van der Duin, 2018). Current efforts to do so are limited; we can do more to make them specific to actor and region, and especially to connect them to conclusions of critical mapping studies.

One resonant body of deliberative engagement work has been conducted by a UK-based network of practitioners who align themselves strongly with the RRI programme. Bellamy and Lezaun (2017) summarizes a 'second wave' of engagements; key examples include Corner et al. (2013), Bellamy et al. (2013), Macnaghten and Szerszynski (2013), and the secondary analysis of McLaren et al. (2016). These works pose themselves as a course correction to a first wave of engagement studies argued to highlight facilitative frames from modeling work, and lock SRM and CDR in as policy options (e.g. Ipsos Mori, 2010 and Mercer, Keith & Sharp, 2011; regard the framing language of Burns et al., 2016). 'Second wave' engagements, then, are kin to critiques of the 'actionable evidence' paradigm of authoritative assessments (see section 3.1, and Owen, 2014), with the same efforts to refocus attention on society's right to be involved in defining the feasibility, risks, and aims of CE. The results of these studies tend to portray public perceptions as critical of CE in comparison to more established mitigation options (particularly of SRM), and as placing a stronger focus on social dimensions of risk to which technical modeling is less amenable. Many other engagements exist that do not self-identify with this normative project, although they—to a less forceful degree—share conclusions regarding perceptions of CE (e.g. Wibeck, Hansson & Anshelm, 2015; Wibeck et al., 2017), as well as problematize procedures of deliberation and constitution of publics (Sugiyama et al., 2017; Cairns, 2019).

A less visible body of work draws inspiration from older branches of 'future studies', as well as the practice of foresight in planning (see Selin, 2008; Barben et al., 2008; Guston, 2014). Several 'single-author scenarios' leverage the logic of experimental futuring to consider contingencies (Bodansky, 2013; Sweeney, 2014; Morton, 2015; Rabitz, 2016). An adjacent literature is tied more to RRI principles, using deliberative stakeholder engagements to generate 'explorative' scenarios that link the imagination of risks to the concerns of participants present (e.g. Banerjee, Collins, Low & Blackstock, 2011), as well as to possible governance mechanisms (Low, 2017; Bellamy & Healey, 2018). Further efforts are emerging in forms of gaming and role-playing (Matzner & Herrenbrück, 2016; Suarez & van Aalst, 2017). There continue to be calls for this brand of foresight to be applied further (Vervoort & Gupta, 2018; Chhetri et al., 2018). But for now, foresight (and gaming) studies are less visible when compared to scenarios generated by modelling, or even other deliberative engagement activity—possibly because of internal debate over the truth-value of scenarios with deliberately rich fictions, and by connection, whether scenarios can act as tool of projection for strategic guidance, or only as a platform for deliberation.

Future engagement work should unlock the potential of deliberative formats currently marshalled under wider RRI practice (Ribeiro et al., 2017, p 93; Chilvers & Kearnes, 2019, p 10). Typical variations of focus groups and participatory forums are low-lying fruit. The potential of games (Vervoort, 2019; Mendler de Suarez et al., 2012) and fiction (e.g. 'climate fiction', Milkoreit, 2016) are underapplied as engagement, role-playing, and futuring tools (see Buck 2019a, which combines elements of both). The resonance of modelling epistemology and scenarios in SRM and CDR assessments should especially motivate RRI to treat modelling not only as a realm of critical inquiry (section 2.3), but as a learning and generative tool (van der Sluijs 2002; Salter et al. 2010) for which we are already beginning to see initiatives (Carton, n.d.; DIPOL, n.d.; FCEA, 2020). One of these (FCEA, 2020) leverages the insights and practices of science fiction, foresight-based scenarios, and integrated assessment modelling for policy information.

3.3 Tensions in RRI practice

RRI practice contests the bounds of debate in climate engineering, but it does so in particular ways. How have some practitioners attempted to reinforce assessment and discourse in their image? How has RRI itself been shaped by activities within climate engineering research and assessment? In what follows, we turn our attention to the effects of this RRI-inspired work, as well as draw out some of the underlying tensions and inconsistencies.

3.3.1 Informing vs. forming social choices

First, there is a tension in RRI practice between what Stirling (2008) distinguishes as 'commitments', or the inevitable '*forming* of social choices' on a novel technology that then manifests as forms of policy, funding, regulation, and liabilities; and 'appraisal', or the *informing* of those choices. RRI practice is dedicated to 'opening up' appraisal, but is less vocal and specific on the formation of commitments. RRI does not preclude the emergence of dominant narratives and ensuing policies—as long as these are not perverse, inequitable, or recklessly enabling; or that they reflect a considered consensus that emerges from sustained engagement with publics and stakeholders deemed relevant (e.g. Stirling 2007 p. 284). And much thinking is dedicated to 'Responsiveness', or adjusting regulatory policies and structures (within governance activities writ large) in light of insights gleaned from 'Anticipatory, Reflexive and Inclusive' assessments (Stilgoe et al., 2013). Yet, this is more a matter of establishing a process for 'responsible' science governance, rather than throwing (or even implying) support behind particular trajectories or visions of development. 'Closing down' can seem like a state of affairs held in abeyance.

Several contexts lend themselves to the slipperiness regarding when the 'right' commitments would and should become entrenched. The generally stated reason is that it is ultimately up to 'society', howsoever defined, to decide. This bears merit, but the shaping role of the researcher in reaching or rejecting such a conclusion is certainly underplayed. The second is pragmatic: RRI activity in CE is currently staffed largely by social scientists with stronger collective expertise in mapping knowledge than policy formation or regime reform, and may not be geared against 'forming' as much as comparatively geared towards 'informing'. A third reason might lie at the heart of RRI as a project descended from STS. What would happen if engagements began to comprehensively reproduce enabling, technocratic frames? To what degree must the RRI practitioner maintain, in the critical tradition, that 'it could be otherwise'?

How are these tensions manifesting in CE discourses? At the broadest level, efforts to forestall the specter of 'mission-driven research' for policy formation may have some partial influence in impeding the formation of concrete policy or trajectories of development. In the absence of policy, RRI studies also give an incomplete portrayal of contestations over 'de facto' governance that primarily assess the activities of a technology's advocates (we return to this later). But RRI work is also showing signs of divergence in the fields of SRM and CDR, reflecting escalating trends that reject the coherence of the 'climate engineering' umbrella.

3.3.2 Enabling CDR, disabling SRM?

Research in SRM and CDR has co-evolved, with overlapping actors and discourses. But while RRI work on SRM remains a cross between generating open appraisal and critical commitments, some RRI engagement in CDR is beginning to reflect enabling frames generated by 'net negative' and 'net zero' emissions in policy conversations. Bellamy (2018), for example, reframes the language of RRI around 'responsible incentivization' with specific regard to CDR, and calls for such incentives 'as an explicit policy goal'—compare this to the language of Bellamy et al. (2013) and Bellamy (2016), which implies extreme caution for framing SRM as an object of policy. The emergence of policy-oriented frames on kinds of CDR in RRI-informed work is—regardless of whether CDR policy might eventually be restrictive or enabling—a stage of permissiveness yet to be granted to SRM.

Several factors may have been facilitative. Heterogeneous arguments for disaggregating the umbrella term of 'climate engineering' (e.g. Heyward, 2013; Boucher et al., 2014; McNutt et al., 2015a; Pereira, 2016; Keith, 2017) have had a functional effect in separating carbon removal from the more controversial baggage of sunlight reflection. Long (2017), Morrow (2017) and Gupta and Möller (2018) argue that the increasing SRM-CDR split in assessment reports has had the steering effect of presenting SRM as a more uncertain prospect than CDR, with the effect that critical social science came late to the latter. The emergence of BECCS in 2C and 1.5C emissions pathways (IPCC, 2014; IPCC 2018) is also normalizing the promise of CDR through the concept of 'net negative emissions' (Beck & Mahony, 2018a; Haikola et al., 2019), with salutary effects for the preceding concept of 'net zero emissions', or carbon neutrality (Geden et al., 2019).

Moreover, there is an increased awareness of BECCS in climate policy, particularly in light of growing aspirations towards carbon neutrality by 2050. This could be a reason for comparatively permissive frames in CDR research. However, there is neither indication of policy uptake beyond target-setting, nor of much literacy in climate decision-making on the shape of carbon removals needed to make 'net zero' plausible. Much assessment is dedicated to filling this knowledge gap, but many studies would likely not identify as RRI-informed, framing themselves as exploring barriers to—or implications of—rollout of BECCS at scale (e.g. Fridahl & Lehtveer, 2018; Gough et al., 2018). These are not necessarily 'reflexive' analyses of knowledge economy as much as socio-politically oriented supplements to calculations of techno-economic and biophysical barriers to CDR deployment (e.g. Smith et al., 2016; Minx et al., 2018; Rickels et al., 2019).

There is an opportunity for RRI-informed activity to ensure that research that does treat CDR as a 'policy object' (Owen, 2014) is not instrumentalized. We should engage with policy-oriented metrics as an imperfect step in debating the challenges of scaling such systems, but practitioners should step up explorations of whether envisioned terrestrial, marine, or technological CDR approaches meet appropriate variations of societal acceptance. RRI and STS engagements with CDR are just beginning. Prior to the BECCS debate, there were few societal and political studies of CDR's implications and knowledge economy, though there is significant empirical research on particular techniques such as forest carbon sequestration and carbon capture and storage (Buck, 2016), and a little on ocean iron fertilization (a discredited form of marine CDR, see Buck, 2018c; Gannon & Hulme, 2018). RRI and STS engagements currently coalesce around terrestrial CDR such as BECCS. One discernable strand of research consists of STS-informed studies on the knowledge economy of IAM work that has led to BECCS' current visibility (Beck & Mahony, 2018a; 2018b; Haikola et al., 2019a; 2019b; Low & Schäfer, 2020; Cointe et al., 2020).

The second relies on analogical comparisons, or surveying and (deliberative) engagement exercises, to source socio-political and ethical concerns. The sprawling UK-based 'Greenhouse Gas Removal from the Atmosphere' Programme contains a project investigating scenarios under which CDR approaches might reinforce the carbon economy ('mitigation deterrence', Markusson et al. n.d.) with stakeholder groups. Bellamy et al. (2019) map perspectives on BECCS policy instruments. Buck (2018a) also explores how (here, rural Californian) perspectives on CDR may come to be shaped by uniquely local, entrenched interests on renewables, and (2016) draws upon analogies with biofuels and forest carbon controversies to point out potentials for land-use conflicts, cash-crop dilemmas for smallholder farmers, or the rise of artificial economies regarding BECCS.

The conduct of RRI in CDR debates, however, could learn positive and cautionary lessons from a comparatively earlier set of RRI engagements in SRM, including the only such concrete governance mechanism—the SPICE 'stage gate' (Stilgoe et al., 2013). More forthright disagreement can be observed between RRI-informed work, and those they perceive as proponents of SRM research who subscribe to an 'actionable evidence' paradigm. These are: stages of research defined by environmental and technical thresholds that demarcate allowed zones for field tests (Parson & Keith, 2013; Parker, 2014), 'mission-driven' climate modelling for assessing physical risk to inform further discussion (Keith & Irvine, 2016; MacMartin & Kravitz, 2019), questioning the certitude of a 'slippery slope' towards deployment, the 'moral hazard' or 'mitigation deterrence', and the ungovernability of a technology with systemic effects (Reynolds, 2014; Keith, 2017), developing governance tenets with a wider focus on technology development (e.g. intellectual property and patenting governance) and deployment (e.g. liability and compensation) (Reynolds, 2019), and research programs with a systems engineering approach (Keith, 2017).

RRI-informed work contests these assumptions on every front. A quick retour is valuable: These emphasize that the technical distinctions between stages and scales are clouded when mapping societal concerns (Stilgoe, 2015), that modeling functionally brackets of socio-political dimensions and sets skewed notions of risk, equity and justice in play (Low & Schäfer, 2019; Flegal & Gupta, 2018; McLaren, 2018), that there are strong indications of 'mitigation deterrence' (McLaren, 2016), or that the characteristics of SRM as projected cannot be managed by democratic processes (Macnaghten & Szerszynski, 2013; Hulme, 2015). Still others highlight the tendency of engaged stakeholders to emphasize socio-political concerns over technical viabilities (Bellamy et al. 2013; McLaren et al., 2016; Bellamy, 2016), that engagement work has to deliberately 'unframe' SRM as a policy object (Corner et al. 2013), and that proponents of SRM research are conducting 'boundary work': setting up the questions such that they are themselves best suited to deliver the answers (Owen, 2014).

At the same time, there are tensions in these critiques. For example, one study—Macnaghten and Szerszynski (2013)—has been critiqued for double standards in characterizing SRM as incompatible with democracy, and for not asking if SRM is any less governable than previous case studies of comparable problem structure that have become accepted regimes of global governance (Heyward & Rayner, 2013; Keith, 2017; Horton et al., 2018). In what follows, we ask if RRI practitioners are engaged in their own boundary work, and how this is shaping activity in SRM and CDR.

3.3.3 Positionalities

Positionality is difficult to grapple with—we ourselves have sympathies towards RRI critiques that can be observed in our respective works.[3] That said, RRI in CE is not even-handed in its pursuit of reflexivity, tending to interrogate—and thereby emphasize—actors outside of their own practice: modelers, engineers, perceived technophiles, the media, and policy and civic participants. The shaping roles of RRI practice in CE

[3] A note on our own positionalities *regarding SRM and CDR* is warranted. Low is wary that these proposals—as concepts as much as scaled systems—may be captured by the carbon economy, following antecedents such as the Kyoto Protocol's 'flexibility mechanisms'; he believes that the resonance of SRM and CDR approaches lies less in the heterogeneous calculations of their technical capacities, and more in what they promise as ideas (e.g. expanding the carbon budget) that trickle down systemically into politics. Buck has a similar concern about capture by the carbon economy / carbon management, especially with direct air capture coupled with enhanced oil recovery, but is also interested in exploring alternative pathways to large-scale carbon removal, as explored in Buck (2019), *After Geoengineering*; she views SRM as worthy of research from a risk management standpoint.

discourses, or self-examination by practitioners in individual studies, are more often caveated than examined in-depth (e.g. Bellamy, 2016; Owen, 2014 p.217).

RRI practitioners engage in the activities that they observe. Van Oudheusden (2014) notes that RRI is typically presented as procedure (where deliberation and democracy lead to more socially robust results) rather than politics (how RRI practitioners intentionally or functionally influence sociotechnical regimes, in the manner of the technically-focused communities they examine). RRI can be seen as efforts to shape 'de facto governance', the informal but forceful norms of scientific conduct (Rip, 2014), which can be linked to 'performativity' (a concept used across the social sciences to inquire after how actions and ideas have imperfectly self-fulfilling effects). Indeed, when RRI's practitioners emphasize the political over the technical in mapping CE's potentials, this is 'boundary work' (Star & Griesemer, 1989), where expert communities contest what is at stake ('benefits and risks' is a popular formulation) and with whom responsibility ultimately lies, by defining problems and solutions in a manner that reflects their own identities and agendas.

RRI's boundary work reverses the polarity of technical, policy-coupled research in three connected trends of 'de facto' governance. First, RRI reformulates definitions of technology performance or viability not as questions of cost, feasibility, and physical impact, but rather in terms of legitimacy gleaned from democratic consent. Second, RRI emphasizes socio-political and ethical questions instead of technical ones; furthermore, pointing out that that there is a limited degree to which societal questions can be shaped by technical knowledge. Third, RRI argues that societal concerns must be explored through open-ended deliberation and imaginative futuring, rather than shaped by proxy via modelling parameters and results. In this way, RRI-informed work (especially in SRM) redefines the terms of debate in such a manner that technical disciplines, or technology advocates, possess less authority to speak to what is at stake than arenas more amenable to RRI-based expertise: stakeholders, 'publics', 'democracy', worldviews, and the social sciences. An important caveat is that these contestations take place to a more forceful degree in SRM conversations, where networks and positionings are more coherent and entrenched.

The argument, certainly, goes both ways: technical, policy-focused networks do this in reverse. The point is that RRI activities in CE rarely reflect on the degree to which key insights—often portrayed as emerging naturally from stakeholder engagements—coincide with the wider aim of producing governance that counters technocratic pressures, or more uncomfortably, with institutional or personal positionings. We are supportive of RRI's aims and wonder if exploring its politics provides ammunition for instrumentalists. But stronger awareness and disclosure of positionality should not erode RRI's value (see footnote 1).

There is, however, an element of speaking to the converted. RRI is currently more successful at marshalling the engagement efforts of critical social scientists, than substantively altering the activities of modelling and engineering communities, industry professionals, policy-makers, or social scientists with more positivistic methods for risk assessment or enabling stances toward R&D. Indeed, it is questionable whether the loose structure of RRI's concepts and approaches is seen as coherent outside of its own community (Ribeiro et al., 2017), and the theoretical and practical challenges of 'deliberation' continue to be debated (Lövbrand et al., 2011; Lenzi, 2019). On questions of positionality and influence, RRI would benefit from increased exchange with practitioners from forms of Technology Assessment (and other longer-running frameworks) that have in the past grappled with relevance and identity, becoming institutionalized or instrumentalized, and the elided politics of their own practice (e.g. Van Est, 2017 and special issue).

This remains a partial review of RRI's constitutive effects in CE. Spaces to watch may include the 'responsible incentivization' of CDR approaches; we might observe if RRI work begins to re-produce or reject the 'policy object' frames currently endowed on BECCS, or if these are inherited by marine-based CDR or direct air capture. RRI, since the SPICE project, has not been re-applied as a concrete governance mechanism, and whether it re-surfaces as part of (small-scale) field tests and pilot projects of SRM or CDR would say much about its resonance. For now, we might note that the concept of 'responsibility' itself becoming the object of boundary work. 'Responsible' research and innovation (or incentivization) claims the word and the opening move in framing it (Stilgoe et al., 2013, p.1569). Keith (2017), however, labels as 'responsible' an SRM research programme centered around systems engineering and stress-testing development and deployment scenarios. Assessments with no inclination towards RRI have used 'responsibility' to reframe governance to their favor (e.g. McNutt et al., 2015a on 'responsible' deployment of SRM, see critique of Morrow, 2017); others invoke RRI tenets, but recommend governance that is still of the mode that RRI criticizes (see Foley et al., 2018).

3.4. Some future steps for RRI practice in CE

Beyond acknowledging positionality, we propose some steps that can be taken in future RRI practice in SRM and CDR conversations, with the goal of asking practitioners to further confront challenges noted earlier.

3.4.1 Use RRI as a lens on the long arc of climate governance

First, we should apply RRI concepts to the definitional politics of CE. This means treating SRM and CDR approaches not strictly as separate, nor holistically as 'climate engineering', but as the latest steps in lineages of sociotechnical climate strategies that were in their time seen as novel. For example, we would not be talking about BECCS if not for land-use management, carbon sinks, and biofuels (Buck, 2016), carbon capture and storage (Markusson et al., 2016), the legacy of eco-neoliberalism (Carton, 2019), or if CDR and SRM had not been framed together for a time as novel interventions in the global climate. The way all these current and historic components have been discussed and managed informs us about BECCS' political economy, as well as avenues for governance. And not only have SRM and CDR co-evolved or been influenced by antecedent sociotechnical systems in climate governance; they have overlapping spheres of actors, concepts, institutions and discourses in the same post-Paris Agreement governance and policy space.

It is increasingly argued that SRM and CDR approaches should be assessed separately, and even as individual approaches, due to different technological, climatic, and political characteristics, and that 'climate engineering' is a term that has lost coherence. RRI-informed assessment should resist fostering an amnesia about 'climate engineering' because it facilitates an instrumentalist tendency towards defining risks and opportunities for particular approaches (e.g. McNutt et al., 2015 a; 2015 b); it should also resist wholly separate treatment as this 'forfeits an opportunity to think about a holistic climate strategy' (Long, 2017).

Rather, exploring SRM and CDR approaches more as 'novel climate strategies' (the concept matters more than the name) allows us to de-emphasize the rigidity of the 'climate engineering' moniker, or, for that matter, SRM and CDR, while recognizing their framing roles. It allows us to more fluidly situate these approaches (and how they are labelled) as their fits with established suites of mitigation and adaptation are negotiated, and it opens up a wider conversation on these approaches' connections to past, present, and future climate strategies. This may seem vague to the reader, who may find a continuing need to scrutinize categorizations obvious, but remain unsure about the usefulness of specific demarcations.

Yet, consider that there are multiple such examples in current climate governance besides what are now termed types of SRM and CDR. A similar kind of uneasy and unfinished fitting has been happening to carbon capture and storage (Krüger, 2017), 'bridging' or 'clean' fossil fuels (Lazarus et al., 2015), and short-lived climate forcing pollutants (Victor et al., 2015)—as was once the case for 'adaptation' (Schipper, 2006). What have the politics of assessment and categorization been in these cases; how have they been performative in policy? To what degree might novel climate strategies be captured by interests in the carbon economy, following examples in the past (McLaren et al., 2019)? How would proposals for kinds of sunshades and carbon sinks unfold alongside these avenues and others in a Paris Agreement era of governance—described as bottom-up, polycentric, and catalytic in intent (Held & Roger, 2018), but potentially be laissez faire, driven by markets and clubs, and rife with externalities (Ciplet & Roberts, 2017)?

3.4.2 Reparative, generative, and situated engagements

In the future, we must more actively connect mappings and interrogations of the knowledge economy with engagements which seek to repair the shortcomings which they map and implicitly critique; and to include local or actor-specific contexts. These are already in RRI's mission statement; our suggestion is to emphasize them for incoming SRM and CDR assessment.

The research mapping the landscape of discourses, actors, institutions, and agendas contesting CE governance has a generally emancipatory intent (section 2.3). These critical analyses, however, can play a more purposefully corrective role, if RRI practitioners more systematically connect them to initiatives that generate narratives and include constituencies based on inequities in knowledge construction (section 2.4), especially in projects emphasizing national or local contexts that would shape particular concerns and avenues for effective governance. Such connection should motivate RRI practice to grapple with the tensions of explicitly generative work, especially between providing a platform for deliberation or for application in concrete governance or technology development processes (Low & Schäfer, 2019, p.8). Foresight work, in particular, comes to RRI from government and business planning, and RRI-informed futuring has to learn how to negotiate with instrumentalist interpretations of its value. Similarly, connections between mapping and generative work in local contexts would more tightly focus the latter. Deliberative engagements based in northern Europe (however unintentionally) give the impression of delivering generalizable insights from some globalized public, while the much smaller set of foresight and scenarios activities has often taken a catch-all, global approach to mapping concerns. Engagement might take different shapes in different contexts; the northern European context has tended to favor mini-publics (e.g. Bellamy & Lezaun 2015), while the American context shows a stronger tendency towards engaging interest groups (e.g. FCEA, n.d.).

In general, we make a plea for RRI practice to operate more often under guiding questions relevant to a specified political context and audience. Modeled deployment schemes, risk scenarios, and governance recommendations are often conceptualized at a global scope; unspecified users of these works are treated functionally as 'benevolent global planners'. High-level and parsimonious approaches have benefits (e.g. Rayner et al., 2013; Long, 2017), but can also create insights divorced from specific politics, as well as policy, funding, and innovation processes (Vervoort & Gupta, 2018). This is not an argument for solution-oriented assessment, or against emancipatory research, or against studies of systemic scope. Rather, a 'hosting' set of structures, worldviews, policy platforms, and political agendas presents a sandbox within which one can pose context-driven but RRI-informed activities, bounding the plurality of imaginaries and stakeholders, and coming down explicitly on the side of embeddedness rather than divorced critique. Morrow (2019), for example, argues that calls for a 'mission-driven' research program (in this case, proposals for SRM research in the US—see Keith, 2017) have to be engaged, and bridging spaces between informing policy and exploring societal legitimacy can be designed. 'Situated' engagement can take place at all levels in contexts that are locally meaningful, whether they be in governmental settings, or community centers, educational institutions, and religious organizations.

We can imagine these activities taking place as part of an assessment or a research programme. Recall the UNEA resolution in the introduction. The status quo in assessment is a multidisciplinary agglomeration of work packages on technical definitions, modelling, politics, legal mechanisms, and governance that are 'separate but equal' (Foley et al., 2018), and that typically treats RRI-informed activity as a segregated component filed into the 'governance' section under 'upstream', 'sub-state', or 'bottom up' processes (e.g. Shepherd et al., 2009; Schäfer et al., 2015). An assessment process grounded entirely in RRI, then, might contain the twinned streams of mapping and generative activities highlighted earlier, and the framework of Barben et al. (n.d.) provides a valuable template. Such assessment would be made relevant to international bodies (the UNFCCC or UNEA), firms and industry (Shell, fossil fuel extractors), national contexts, and regions with histories of coordination (the EU, or small island states). For example, within the context of the EU (where both authors have studied and worked), the mapping stream would have to account for specific historic discourses and commitments (e.g. support of the 2C target, the precautionary principle), contextual politics (e.g. heterogeneous energy landscapes within the bloc; trends towards pluralism and fragmentation), and review actors and perspectives both privileged and missing. Engagement and futuring activities would account for the fact that assessments have largely taken place within a handful of wealthy northern European states with comparatively strong climate ambitions (Bellamy & Geden, 2019; Biermann & Möller, 2019; Stephens & Surprise, 2020). Tying these insights to concrete governance would require understanding the EU's coordination of research funding, and policy in climate, energy, and innovation (Policy for research and technological development, 2019), as well as the relevance and agendas of its national and regional regulatory structures.

One can ask, given the emphasis of RRI on the situated, how such processes are scalable. How might an ecosystem of context-specific, embedded conversations be put together in a systemic manner? Most RRI practitioners would argue that engagement does not need to be universal to improve the quality, robustness, and social attunement of research, but scaling engagement is perhaps important for securing planetary legitimacy. There are precedents here; context-specific assessment in climate governance is frequently incorporated into larger summaries. We can point to the IPCC's Working Group II on impacts and vulnerabilities—which not only have to be highlighted as specific to region and capacity, but in metrics and concepts that allow comparability across context, and be communicable at an imperfect aggregate level. Indeed, few insights are so unique as to have no wider relevance. Perspective mapping done amongst Finnish Laplanders (Buck, 2018b) might, for example, have broader generalizability for rural communities, the indigenous, or Arctic polities. Buck (ibid.) also argues that concerns explored here were reflective of a global imaginary rather than a specifically local one.

3.4.3 Design governance beyond research and assessment

The first clear engagement of RRI in climate engineering debates—the 'stage gate' of the SPICE 'test bed' (Stilgoe et al., 2013)—was a concrete governance mechanism and process. It might seem odd that there have since been no further examples. In SRM, there has been a lack of field demonstrations since SPICE to direct such efforts, and an upcoming small-scale experiment planned by Harvard researchers (Dykema et al., 2014) appears less engaged by RRI practitioners. CDR, through BECCS, has overtaken SRM as a topic of policy-oriented conversation, but RRI practice has similarly not engaged with (the albeit limited number) of projects and pilots that develop the hardware and components of CDR (e.g. BECCS or direct air capture) systems.

Rayner (2017) described the state of CE as a 'research impasse', where technologists were waiting for a more permissive climate, while social scientists concerned themselves with mapping imaginaries. This formulation is generous to technologists and unkind to social scientists, but it seems accurate that RRI practice has since SPICE pragmatically treated *research itself as a form of governance*. There is, in our estimation, nothing wrong with this avenue of activity—imaginaries are resonant, and interrogating the evidence and actors that underpin them is, as we have noted, its own form of 'de facto' governance.

But there is also room to explore proposals for concrete governance mechanisms and processes—these should not be seen as facilitative, but anticipatory. 'Principle and protocols' remain an adaptable governance suite: the 'Code of Conduct' of Hubert (2017) integrates principles of 'responsible' research with international legal norms and is a living document iteratively developed with stakeholder engagements. We can re-examine the value of information clearing houses and other kinds of disclosure mechanisms (Craik & Moore, 2014). RRI practice must also develop processes that grapple with specifics of technical hardware development, such as tying R&D to incentives that prevent fudging on mitigation (McLaren, et al., 2019), or patents and intellectual property rights (Parthasarathy et al., 2017). Not enough attention has been paid, since the SPICE 'stage gate', to concrete 'provisions to detect, slow, or stop lock-in' at stages from conception to implementation (McKinnon, 2018). And all of these questions can be similarly be linked to and informed by the insights of engagement and critique, and adapted to particular institutional, sectoral, or political contexts and agendas.

3.5 Conclusion

Responsible research and innovation activity has appeared in climate engineering over the past decade in the forms of assessment processes, principles and protocols, critical mappings, and deliberative engagements. Right now, sunlight reflection methods in particular face a research impasse, and have no governance; the recent 2019 attempt at the UN Environment Assembly highlighted the challenge of even agreeing to assess it. But it is possible this will change: the IPCC is considering SRM in its Sixth Assessment Report, and the US National Academies of Sciences are studying a research agenda. Carbon dioxide removal, meanwhile, is gaining in research and attention.

The stakes are thus high for developing responsible research and innovation in both these climate response approaches. RRI has arguably been moderately successful as a corrective in the previous decade's context—when SRM was a fringe idea with very little research funding, and climate change was not yet considered an 'emergency' by mainstream thinkers. We cannot take for granted, however, that it will successful in opening up debate or foregrounding social dimensions of these climate responses in future contexts. Long and Blok (2017), for example, suggest that the values associated with current forms of populism conflict with values central to RRI, and even suggest that a lack of RRI may have aided the populist rise, critiquing RRI scholars for being inadequately critical of the economic system. They call for a 'resurgent RRI', more critical and assertive, which can question the political economic context in which RRI is performed (ibid.). Indeed, climate engineering research in particular would benefit from a 'recalibrated' RRI. Going forward, applying RRI to climate intervention can help to produce assessments that are grounded in RRI which map not just technologies and narratives, but actors involved. It can help to produce concrete governance mechanisms, not just serve as de facto governance by governing research. And an RRI approach can help in the holistic assessment and discussion of all climate responses, not just solar geoengineering or carbon removal discretely, which can inform a more intelligent and robust climate response strategy than when these are parceled out without relationship to each other, mitigation, or adaptation.

Chapter 4

Delaying Decarbonization: Climate governmentalities and sociotechnical strategies from Copenhagen to Paris

An era (2005-2015) centered around the Copenhagen Accord saw the rise of several immature sociotechnical strategies currently at play: carbon capture and storage, REDD+, next-generation biofuels, shale gas, short-lived climate pollutants, carbon dioxide removal, and solar radiation management. Through a framework grounded in governmentality studies, we point out common trends in how this seemingly disparate range of strategies is emerging, evolving, and taking effect. We find that recent sociotechnical strategies reflect and reinforce governance rationalities emerging during the Copenhagen era: regime polycentrism, relative gains sought in negotiations, 'co-benefits' sought with other governance regimes, 'time-buying' or 'bridging' rationalities, and appeals to vulnerable demographics. However, these sociotechnical systems remain conditioned by the resilient market governmentality of the Kyoto Protocol era. Indeed, the carbon economy exercises a systemic structuring condition: While emerging climate strategies ostensibly present new tracks for signalling ambition and action, they functionally permit the delaying of comprehensive decarbonization.

Published as: Low, S. and Boettcher, M. (2020). Delaying Decarbonization: Climate governmentalities and sociotechnical strategies from Copenhagen to Paris. *Earth System Governance.* DOI: 10.1016/j.esg.2020.100073

- Low: Conceptualization; data curation; formal analysis; writing-original draft; writing-review and editing
- Boettcher: Formal analysis; writing-review and editing

4.1 Introduction

In 2005, a long-brewing sea change in global climate governance became visible. The Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) formally began negotiations for an agreement needed to succeed 1997's Kyoto Protocol. Now, a combination of historic grievances and contemporary challenges would swiftly stall progress on a new agreement. A large literature recounts how these efforts culminated disastrously at the 2009 COP in Copenhagen, and were resurrected with guarded optimism through the 2015 Paris Agreement (e.g. Falkner, 2016).

Many works have traced the history of climate governance in terms of institutions, negotiation agendas, and factional interests (e.g. Gupta, 2010), or hidden dynamics underlying more visible activities and alignments (e.g. Aykut, 2016). This paper is situated within the latter, and poses an account of recent climate governance as a history of emerging sociotechnical strategies designed to address climate change (e.g. Markusson et al., 2017). We focus on a 'Copenhagen' era (2005-2015) centered around the 2009 Copenhagen Accord, but that we stretch to include its negotiation, as well as evolution into the Paris Agreement.

The Copenhagen era saw the rise or consolidation of a range of sociotechnical climate strategies currently at play: carbon capture and storage (CCS), the forest emissions crediting mechanism of REDD+, next-generation biofuels, shale gas, short-lived climate forcing pollutants (SLCPs), solar radiation management (SRM) as a kind of 'climate engineering', and carbon dioxide removal (CDR) as novel carbon sinks. In this paper, we present an interpretative review of secondary literature, through a framework grounded in governmentality studies, to explore common trends in how this seemingly disparate range of strategies is emerging, evolving, and taking effect.

We make three arguments. Firstly, recent sociotechnical strategies reflect and reinforce governance rationalities emerging during the post-Kyoto Copenhagen era. Secondly, distinct characteristics link various sociotechnical systems to each other, and to the resilient market governmentality of the Kyoto era. Thirdly, the carbon economy exercises a systemic structuring condition. While emerging climate strategies ostensibly present new tracks for signalling ambition and action for reducing some palette of greenhouse gas emissions, they functionally permit the delaying of comprehensive decarbonization.

The following section outlines our conceptual framework, synthesizing insights from governmentality studies in global environmental governance, science and technology studies (STS), and critical political economy. Section 4.3 details our analytical approach. Sections 4.4 and 4.5 assess the fit between the Copenhagen era's governmentalities and sociotechnical climate strategies in a two-part analysis – section 4.4 maps the strategies sequentially, while section 4.5 steps back to map overarching relationships between these strategies in their rationales and practices. Section 4.6 concludes that as we move into the implementation of the Paris Agreement, understanding how climate strategies are shaped by persistent structuring conditions may help to develop guardrails to avoid repeating past mistakes.

4.2 Conceptual framework: Sociotechnical strategies, governmentalities, and 'fixing'

Following STS, we refer to various Copenhagen-era strategies as 'sociotechnical' infrastructures that combine technological hardware with the software of societal contexts, beliefs, and choices. 'Sociotechnical strategies' is a terminological compromise on two counts. We recognize that what we call sociotechnical (e.g. carbon markets) includes socio-ecological (e.g. forestry management) practices, and that 'strategies' is an imperfect attempt to capture a mix of scaled (e.g. shale gas), immature (unscaled beyond the project level, e.g. CCS), and imagined systems or interventions (e.g. SRM).[4] But our focus is not on precise types, stages, or scales. Rather, what bridges these strategies across their scales of implementation is their unfinished nature, and despite this – or possibly, because of it – their reified roles in climate discourse and policy.

This brings us into contact with the STS literature on 'expectations' (Brown, Rappert & Webster, 2000) and a more recent one on 'sociotechnical imaginaries' (Jasanoff & Kim, 2015, eds), which highlight the forcefully promissory nature of envisionings and projections of a technology's future. The latter, following Jasanoff's (2004) idiom of 'co-production', argues that polities design technological systems to mirror what they desire societally. Building on initial explorations of how these concepts can be applied to limited suites of climate strategies (e.g. Hansson, 2011; Markusson et al., 2017), we expand the scope of inquiry to the recent history of climate governance, and to tie them to that era's structuring rationalities (a comparable effort is McLaren & Markusson, 2020).

Here, we refer to 'governmentality', a Foucauldian concept describing the logics and practices by which societies make themselves subject to control. Governmentality studies expand the climate governance literature's purview from states and institutions to strategies and practices dispersed at multiple levels (Okerere et al., 2009), and explore these activities as reflections of systemic understandings that coordinate governing of the climate, the market, polities, and even the individual (Stripple & Bulkeley, 2014, eds).

We therefore see governmentalities as ensembles of climate governance rationalities, institutions, and strategies – in this paper, our main focus is on emerging rationalities, and how these condition sociotechnical strategies. Governmentalities and Jasanoff's 'imaginaries' overlap; both reflect some overarching rationality that manifests, respectively, as systems of (environmental) governance or techno-science. Our paper reflects a connection of these literatures. Indeed, governmentality and STS studies are part of the same wave of exchange between global governance studies and critical disciplines, and both governmentality (Stripple & Bulkeley, 2014, eds) and STS (Miller, 2004; Hulme & Mahony, 2010) approaches encourage the analyst to be aware of the rationales and processes by which 'climate change' – as a problem and adjoining solutions – is constructed.

[4] Using 'strategies' might connotate agency, or deliberate intent by particular agents, rather than the 'systemic structural conditioning' referenced in the introduction. This is not our intent: We could also have used neutral terms like 'practices' or 'activities', but chose a more overarching term commensurate to the scale of global climate policy. We also do not intend to come down definitively on either side of the agent-structure debate. This paper *emphasizes structures* and how choices and actions to address climate are thereby conditioned, but climate governance is a fluid interplay between the two.

We speak to governmentalities that came to animate climate governance in the extended period surrounding the 2009 Copenhagen Accord (2005-2015). We rely on seminal work by Bäckstrand and Lövbrand (2006; 2016), who describe how Kyoto-era forest projects reflected discourses that remained resonant as political rationalities long into the Copenhagen era. Two of these retain importance in our paper's account: *'green governmentality'* describes the globally-focused and managerial rationality that underpinned the formation of the Intergovernmental Panel on Climate Change (IPCC), the UNFCCC, and the Kyoto Protocol; coupled with *'ecological modernization'*, the socialization of environmental governance within neoliberal market logics (ibid).

Over a decade, Kyoto's governmentalities morphed to account for the evolving demands of global politics. The shift in the regime's emphasis from operationalization of the Kyoto Protocol (1997-2007) to the Copenhagen era's search for a post-Kyoto framework was marked by numerous adjoining challenges: the rise of emerging economies; the US withdrawal from Kyoto in 2001; the erosion of multilateralism in post 9/11 geopolitics; the financial crisis of 2007-2009 (Ciplet et al., 2015). In the leadup to the Copenhagen COP - where a post-Kyoto framework was to have been agreed upon - it was clear that collective confidence in the UNFCCC had broken down. Key issues included global targets, a re-drawing of where responsibilities for emissions reductions would now lie, and issues of finance and adaptation in most vulnerable states; with a fragmenting global politics and austerity-driven lack of resources hanging over the regime (Gupta, 2010; Held & Roger, 2018). Layering Bäckstrand and Lövbrand's papers with concurrent analyses, we note that both governmentalities began to converge upon a set of overlapping characteristics that is still being cemented today.

'Green governmentality'- the Kyoto-era's regulatory, top-down, compliance-based logic - was rooted in a post-1970s tradition of centralized environmental regime design. With the Kyoto Protocol's failings increasingly exposed, and short on resources and attention, pre-Copenhagen COP negotiations pivoted from 'making Annex I larger' towards voluntary, non-binding, 'nationally determined' efforts (Held & Rogers, 2018). This arrangement attracted support from states on either side of the Annex I divide. The ensuing 2009 Copenhagen Accord is recognized today as the in-between stage that was tweaked and formalized as the 2015 Paris Agreement's pledge-and-review system (ibid; Falkner, 2016). This evolution reflects the fragmentation of climate governance towards what has been problematized as 'a regime complex' (Keohane & Victor, 2011), 'polycentricism' (Dorsch & Flachsland, 2017), or a 'global fractal' (Bernstein & Hoffmann, 2019). Discussion mirrored discourse of the era, still familiar today: 'coalitions of the willing', as well as all manner of public-private and multi-level networks. But its potentials, then as now, were in flux. For some, Kyoto's logics had always needed to cater to more plural perspectives, sites, and activities than could be managed by an IPCC-UNFCCC duopoly (Prins & Rayner, 2007). For others, the cloud overshadowed the silver lining, with Copenhagen representing an 'enhanced status quo [in which] states did what they were willing' (Held & Rogers, 2018) in a system of 'shared unaccountability' (Ciplet & Roberts, 2017).

Broadening the sites and objectives of post-Kyoto governance in a time of austerity also multiplied the rationalities by which the Copenhagen-era regime was kept alive. Dovetailing with the trend towards polycentrism, there was an escalation of 'co-benefits' sought between addressing climate change and other governance issues, regimes, and sectors – from energy and food security, to land-use forestry, to air pollution and health (Bäckstrand & Lövbrand, 2016; Bain et al., 2015; with Mayrhofer & Gupta, 2016 indicating this was a wider governance trend). Relative gains were sought to sustain the negotiations agenda at the UNFCCC (Dimitrov, 2010; Khan & Roberts, 2013). Rationalities on the value of 'bridging' and 'time-buying' options began to solidify, ranging from transitional fuels that might temporarily substitute for high-carbon fuels on route to renewables, to wider strategies that might reduce climate impacts and allow room for polities and economies to adapt and transition in the near term (Buck et al., 2020). Appeals to an array of nongovernmental stakeholders and to the world's 'most vulnerable' became an increasing anchor for relevance and legitimacy (Bäckstrand & Lövbrand, 2016).

'Ecological modernization' converged upon the same characteristics. The marrying of economic imperatives and environmental ambitions through the Kyoto Protocol's carbon-accounting and trading 'flexible mechanisms' (e.g. emissions trading schemes and the Clean Development Mechanism, CDM) took on the trappings of emerging 'green economy' conversations, emphasizing low carbon transitions as part of co-benefits with health and energy security, to be executed by an ecosystem of clubs and networks, and with increased reference to civil society and 'the most vulnerable' as part of the new polycentricism (Bäckstrand & Lövbrand, 2016). It remains unclear if and how market governmentalities (Hajer, 1995; Bernstein, 2001; Paterson & P-Laberge, 2016) are adapting outward from Kyoto's focus on carbon accounting and trading. Michaelowa et al. (2019) notes that carbon markets have not, since a 2012-2014 crash due to the financial crisis, excess credits, and low governmental support, recovered in visibility. 'Ecological modernization' might be ripe for a new mode that prioritizes low-carbon transitions. Yet, for many, the long-term trend is less optimistic: because the Paris Agreement institutionalizes the 'voluntarism' of Copenhagen, market mechanisms, reliance on private sector funding, innovation-facing rhetoric coupled with regulatory softening, and club-based decision-making can only intensify (Bernstein et al., 2010; Krüger, 2017; Ciplet & Roberts, 2017; Blum & Lövbrand, 2019).

The prevalence of both governmentalities is reflected in various literatures. The top-down, regulatory model of Kyoto is broadly acknowledged (Gupta, 2010; Held & Roger, 2018), and came to be the subject of critique as action endemically fell short of pledges (Prins & Rayner, 2007); the potentials of a turn towards polycentric governance remains debated (Ciplet & Roberts, 2017; Bernstein & Hoffmann, 2019). The market rationality in climate governance reflecting carbon capitalism as a hegemonic social system (Oels, 2005; Lövbrand & Stripple, 2011) is also the subject of liberal environmentalism, which explores norms (Bernstein, 2001), and climate capitalism or commodification, reflecting a vast political economy literature on carbon's marketization (Paterson & P-Laberge, 2016).

A characteristic of these governmentalities – particularly 'ecological modernization' – is not tackled by Bäckstrand and Lövbrand, but is the subject of literatures grounded in critical strands of geography, political economy, and STS. Emerging strategies – for example, novel carbon sinks, or sunlight reflection methods – are argued to present systemic disincentives for reducing emissions (McLaren, 2016) or reflect politics and discourses of delay (Carton 2019; Lamb et al., 2020), by acting as 'fixes' for the carbon economy and its preferred modes of climate governance (Markusson et al., 2018). McLaren et al. (2019) issues a provocation to inquire after these structural imperatives beyond recent debates on 'climate engineering'; this forms a strong motivation behind our study. According to this perspective, the animating logic of numerous climate governance strategies has arguably been to provide a functional, short-term 'technical fix': to circumvent deep-lying societal and economic structures through technical or biophysical solutions (Nightingale et al., 2019; an original definition comes from Weinberg, 1967). Such fixes, in effect, prolong the systemic 'lock-in' of the carbon economy at a variety of sites and scales (Unruh, 2002; Urry, 2014; Røttereng, 2018; Nightingale et al., 2019).

A number of recent works build on Harvey's (1982) interpretation, which considers how 'spatio-temporal' fixes 'reconfigure geographies' to delay global capitalism's tendencies toward crises. Carton (2016) makes the case for carbon markets as an exemplary fix, and notes that carbon removal and sunlight reflection suites of climate engineering similarly promise to 'slow the rate of decarbonization' (Carton, 2019). Markusson et al.'s (2018) 'cultural political economy' model makes significant contributions. New fixes (e.g. novel carbon sinks) are arguably conditioned by and preserve the rationalities of pre-existing ones (e.g. carbon accounting and trading); moreover, the promissory nature of an imagined sociotechnical system, as much as implemented, scaled-up systems, can play as great a role in reflecting, legitimizing, and entrenching market environmentalism (ibid). Røttereng (2018) calls this 'symbolic signalling', where new tracks of signaled ambition substitute for actual implementation. The array of imagined and immature strategies of the Copenhagen era can, following Carton (2019), thus be seen as a 'mobilization of the future to legitimise and reproduce the present' (p.764).

Literatures on 'lock in' and 'fixes' follow critical (often, post-Marxist) traditions, but we see value in a looser adherence to their generalizable insights, and seek a working definition to that effect. We note several intersecting criteria through which a sociotechnical strategy – imagined, immature, or scaled – can embodying logics of fixing. Firstly, a fixing strategy primarily maintains infrastructures and rationalities for the exploitation and usage of carbon resources, often referencing the pragmatism of avoiding or easing profound changes to the carbon economy. Examples range from the sectoral to the systemic; in later sections, we specify ground-level, tangible examples whenever possible. Secondly, sociotechnical strategies can be as operative through framings (via projections and promises), as through implementation in industry practice or institutionalization in governmental policy (Markusson et al., 2017; Røttereng, 2018; Carton 2019). Thirdly, strategies benefit from dovetailing with dominant market-facing rationalities entrenched during Kyoto Protocol era. Carbon accounting and trading mechanisms in particular, and certain emerging fuels and technologies, became or are becoming prominent because they are calculated as cost effective, and create additional opportunities for hype and the accumulation and re-distribution of capital (ibid). Fourthly, fixing strategies perform two kinds of 'substitutions' in climate ambitions. One presents nearer-term opportunities for the reduction of a palette of greenhouse gases (GHG), emerging proxies defined by global temperature increase, or kinds of climate-related harms – but that functionally put off strategies for long-term, comprehensive reductions in the use of conventional carbon fuels. The other comes from the emergence of seeking co-benefits with other areas of governance: success no longer stems solely from achieving goals and metrics defined by the climate regime, but from a hazier balance of interests between dilemmas and trilemmas of global issues.

Drawing upon these works, we developed a set of preliminary analytical concepts, as outlined in table 1, to conduct a consolidative mapping of how governance rationalities and logics of fixing manifested in sociotechnical strategies geared towards climate governance between 2005 and 2015. The following section outlines our iterative analytical approach before the results of our analysis are presented.

Table 4.1 Emerging rationalities from Kyoto to Copenhagen eras

<table>
<tr><th>Governmentalities of Kyoto era</th><th colspan="2">Emerging rationalities in the Copenhagen era</th><th>'A fixing strategy …'</th></tr>
<tr><td rowspan="2">Green Governmentality: a post-1970s tradition of centralized and managerial environmental regime design</td><td>Polycentrism or fragmentation of climate governance in a time of austerity; reflects wider governance trends</td><td rowspan="5">Rationalities overlap and reinforce each other in ways specific to each sociotechnical strategy – see section 4, table 4.2.</td><td>… primarily maintains infrastructures and rationalities for the exploitation and usage of carbon resources, often referencing the pragmatism of avoiding or easing profound changes to the carbon economy.</td></tr>
<tr><td>Co-benefits with economy and development, energy and food security, forestry, air pollution</td><td>… is operative through projections and promises as well as implementation in industry practice or institutionalization in governmental policy.</td></tr>
<tr><td rowspan="3">Ecological modernization: cost-effective, market facing climate governance based on offsets and credit trading</td><td>Time-buying: easing carbon transitions, dampening near-term climate impacts, catalyzing more deep-lying mitigation</td><td>… benefits from dominant market-facing rationalities entrenched during Kyoto era.</td></tr>
<tr><td>Relative gains: lower-hanging fruit on the negotiations agenda to sustain momentum</td><td>… presents nearer-term opportunities for the reduction of GHG or emerging proxies harms – but that functionally delays deep-lying mitigation.</td></tr>
<tr><td>Appeals to vulnerable demographics and civil society as anchors for legitimacy</td><td>… no longer needs to mark success solely from achieving climate goals and metrics, but from a hazier balance of interests between global issues.</td></tr>
</table>

Column 1 describes two governmentalities (ensembles of governance rationalities and sociotechnical strategies) of the Kyoto Protocol era (Bäckstrand & Lövbrand, 2006; 2016). Column 2 describes emerging rationalities in the Copenhagen era, emphasizing that these are not mutually exclusive, and reinforce each other in ways specific to different sociotechnical strategies. Column 3 describes elements of 'fixing' the carbon economy, or carbon 'lock-in' that can be embodied by entwined governance rationalities and sociotechnical strategies.

4.3 Analytical approach: Interpretative review

For our mapping of the ways in which governance rationalities and logics of fixing manifested in sociotechnical strategies between 2005-2015, we conducted an interpretive review of a broad range of secondary analyses – qualitative, multidisciplinary interrogations of the emergence and implications of more limited groupings of strategies (for example, on biofuels alone, or carbon sinks). We sourced these materials via a keyword search of Google Scholar using the general search terms 'sociotechnical strategies', 'sociotechnical systems', 'climate strategies', 'climate governance strategies', and 'climate technologies', as well as search terms specific to each strategy or system (Kyoto's flexibility mechanisms, CCS, REDD+, next generation biofuels, shale gas, SLCPs, CDR, SRM). Analyses on conventional fossil fuels, renewables like solar, wind, and geothermal, energy efficiency, conventional and novel nuclear, and adaptation strategies provided valuable context, but do not form the bulk of analysis. Our data collection process was based on the principle of 'theoretical sampling' borrowed from Grounded Theory (Glaser & Strauss, 1967). According to this principle, data is collected in parallel to analysis and continues until 'theoretical saturation' is reached – the point at which all analytical concepts are well-represented and the addition of new materials begins to reiterate the same information (ibid). We do not claim that this process resulted in a comprehensive meta-review of all literature on this topic. Rather, we present an interpretative review which critically explores how synthesising insights from governmentality, STS, and political economy can contribute to understanding the emergence and evolution of sociotechnical climate strategies.

Our interpretative review process involved both authors independently undertaking a structured reading of the articles included in the analysis on the basis of the preliminary analytical concepts (Table 4.1). The review was an iterative process, with the analytical categories being revisited and consolidated as the analysis progressed. Specifically, we mapped how governance rationalities and logics of fixing were reflected in the ways various sociotechnical proposals were framed as part of assessments, projections, and promises; and where relevant, how they were implemented in partially-scaled systems, or institutionalized on resonant policy platforms. We inquired after how the means and ends of a particular system were conceptualised at their upstream stages (e.g. Brown et al., 2000). In doing so, we asked after their promissory roles in climate politics – how sociotechnical proposals backed an envisioned state of climate governance, and how that envisioning was recursively used to rationalize technological development. As an indicator of where certain rationalities and logics became comparatively resonant, we noted if they came to undergird existing policy platforms or projects and infrastructures in the process of being scaled up. Based on the mapping of these individual elements, we then asked if and how these emerging sociotechnical strategies reflected the governmentalities of the Copenhagen era. The following section details the results of this interpretative review process.

4.4 Analysis: Sociotechnical strategies of the Copenhagen era

In what follows, we undertake a two-part analysis. Here (section 4.4), we look at the following eight sociotechnical strategies in turn: Kyoto's flexibility mechanisms, CCS, REDD+, next generation biofuels, shale gas, SLCPs, CDR, and SRM. We match them to governmentalities held over from the Kyoto era of 1997-2005 (green governmentality and ecological modernization) as well as rationalities that gained in visibility during the Copenhagen era of 2005-2015 (polycentrism, co-benefits, time-buying, relative gains, and appeals to the vulnerable). The reader can view a more summarized account of this section in Table 4.1. In section 4.5, we step back to map overarching patterns of the relationships between these systems.

4.4.1 Kyoto's flexibility mechanisms

We begin by highlighting the ongoing significance of carbon accounting and trading mechanisms that marshalled much of the Kyoto Protocol's negotiation and operationalization. Dubbed the *'flexibility mechanisms'*, these were framed by the US and its allies as a means to reduce near-term stress on transitioning the carbon economy by incentivising the most cost-effective ways to reduce emissions, and by allowing actors to trade credits derived therefrom. The result was a widespread use of carbon offsetting. The mechanisms consisted of carbon markets (the most prominent was the EU Emissions Trading Scheme, EU-ETS), alongside Joint Implementation (allowing cooperation between developed states), and the Clean Development Mechanism (CDM), which allowed Annex I countries to receive tradable credits (including the EU-ETS, from 2004 onward) from emissions reductions projects in the developing world.

Carbon offsetting and credit trading was the original manifestation of the cost-effective, market-facing logics of climate governance of the Kyoto period (centrist reviews include Newell & Paterson, 2010; Calel, 2016; Paterson & P-Laberge, 2017; Michaelowa et al., 2019). They leave a complicated and unfinished legacy: engaging industry and finance at multiple levels with climate governance, and keeping heavy carbon consuming and extracting states on board with COP ambitions (Newell & Paterson, 2010). Yet, they may have retarded Annex I efforts to take on more comprehensive domestic emissions reductions. Offsetting and trading served as significant – though not exclusive – means by which Annex I states attempted to meet their commitments under the Kyoto Protocol, enjoying a 'gold rush' period of investment and capital creation between 2006 and 2011 (Michaelowa et al., 2019; Lövbrand et al., 2009), but encouraging 'cheap and easy fixes' with limited potential for sustained, structural change (Calel, 2016; Carton, 2016; Ciplet & Roberts, 2017). Both the EU-ETS and CDM lie dormant currently, following a 2012 collapse due to the aftermath of the financial crisis and a fall in US and EU governmental support (Michaelowa et al., 2019). Some fault, tellingly, lies in abuse of the underpinning rationales of market mechanisms: the EU-ETS was flooded by 'hot air' credits from Russia and Ukraine (ibid). Lack of oversight in the CDM, meanwhile, created perverse incentives for false accounting and generation of credits (Schneider, 2009), and additionally often failed to create projects with development benefits in the hosting country (Olson, 2007).

For a time, some emerging sociotechnical proposals of the Copenhagen era benefited from conforming to neoliberal rationalities, and more concretely, tied into accounting and trading structures. Yet, as conditions pushed climate governance towards polycentrism (recall Ciplet et al., 2015), knock-on rationalities would also be catered to. A suite of climate strategies exemplifying this direction of travel described *new arrangements of carbon sinks*.

4.4.2 Carbon capture and storage

Carbon capture and storage (CCS) came to prominence around 2005 as the subject of an IPCC Special Report. Portrayed by advocates as proven in (technical) concept, ripe for upscaling, and indispensable for meeting future emissions targets (Hansson, 2011), CCS was from the beginning tied into existing industry, investment, and – importantly – plans for international credit trading (Krüger, 2017). As a supplement that would not fundamentally alter the carbon economy, the idea of CCS was aided by an additional framing as a feasible 'bridging' option for easing, or buying time for, the transition of entrenched carbon infrastructures; and as a catalyst for more ambitious actions in the future (Bäckstrand et al., 2011; Hanson, 2011; Markusson et al., 2017; Krüger, 2017). CCS did not go uncontested: the 'bridging' framing was opposed as an example of 'lock-in':

an excuse for continuing carbon dependence, where incentives and resources would be reduced for renewables, and 'like nuclear… [be] a techno-fix for an immediate problem with long-term negative consequences' (Bäckstrand et al., 2011). Indeed, CCS was only included in the (by then, recognizably flawed) CDM in 2011, which coincides with the winding down of the Kyoto mechanisms. This framing juxtaposition becomes – and remains – a theme for many incoming sociotechnical strategies.

A significant aspect of CCS is that it has, for all its alleged potential, never been scaled. The bulk of large-scale CCS projects have emerged as an adjacent suite of *carbon capture and utilization in enhanced oil recovery (CCU in EOR)*, where emitted carbon is reused to expand the operational lives of existing oil fields. CCU in EOR has potential for 'technology spillover' back to CCS; yet it represents a downscaling of the original ambition, operationalised because it extends existing carbon extraction infrastructures (Markusson et al., 2017). For some, policy has failed to support CCS development in carbon markets or taxes (Scott et al., 2012; Haszeldine et al., 2018).

For others, the failure of policy is indicative: CCS serves its purpose as a promise (Markusson et al., 2018; Røttereng, 2018). In rhetoric, CCS is, but for some willpower, a readily-deployable 'bridge'. Yet, a clearer marker of its significance is that in investment and policy (or lack thereof), CCS functions most powerfully as the idea that atmospheric GHGs can be decoupled from the carbon economy (Hansson, 2011, Markusson et al., 2017; Krüger, 2017). Indeed, 'CCS-ready' serves as a legitimizing standard for new plants (Krüger, 2017), and CCS is heavily built into IPCC emissions scenarios that map pathways towards ambitious climate targets (Beck & Mahony, 2018). The latter becomes significant later, as we discuss schemes for carbon dioxide removal.

4.4.3 REDD+

Another emerging arrangement surrounding carbon sinks was based on 'reducing emissions from deforestation and forest degradation' (REDD+), which evolved into a mechanism for financing the reduction of forest emissions in developing countries.[5] REDD+ provides a structure for actors in developed countries to finance 'verified emissions reductions' (VERs) in developing, rainforest-heavy nations for managing a basket of practices that grew with each COP between 2005 and 2011 – eventually, deforestation, degradation, conservation and enhancement (Hein et al., 2018; Cadman et al., 2016). At the same time, forestry and land-use management is an old thread of conversation at the UNFCCC, with REDD+ negotiations (2005-2011) building on preceding negotiations on afforestation and reforestation, and their prospective inclusion in the CDM (2001-2004).

REDD+ represented the emergence in the 2000s of 'co-benefits' with other governance issues; here, between climate, local development, and biodiversity (Turnhout et al., 2017; Eliasch, 2008). Co-benefits also dovetailed with economic rationalities: managing forestry, particularly when these manifested as forest carbon projects in the developing world, was less costly and disruptive for developed countries than conventional mitigation efforts (Hein et al., 2018). A sense of pursuing relative gains – lower-hanging fruit on the agenda for sustaining the UNFCCC's visibility and relevance – became more important in the period marking fractious post-Kyoto

[5] REDD+, as a project-level instrument, should not be confused with UN-REDD, which is a multi-lateral programme coordinates and builds capacity for various forest management practices.

negotiations; REDD+ negotiations and post-Kyoto talks both began in 2005. Moreover, forestry and land-use management had long been a track of UNFCCC negotiation that represented a balance of interests between the US and allied states seeking access to offsets, and forested developing nations seeking access to finance (Boyd et al., 2008).

In that vein, REDD+'s credit accounting structure reflects the resilience of 'market-based conservationism' (Hein et al., 2018; see also Turnhout et al., 2017). At the same time, REDD+'s VERs cannot (for now) substitute for domestic emissions reductions in donor states; it is unclear whether REDD+ will transition to a marketized offset mechanism or remain a financing instrument (Cadman et al., 2016). Recall that afforestation and reforestation had been included in the Kyoto Protocol's CDM; without the offsetting aspect, commentators have questioned the functional benefit of supporting REDD+ for developed states. Røttereng (2018) argues that this is evidence of a fix: REDD+ is virtue signalling for carbon consuming and extracting states that distracts from their actual agendas, with the same collection of states showing strong rhetorical support for both REDD+ and CCS as promissory carbon sinks.

4.4.4 Next-generation biofuels

It was not just (marketized) carbon sinks that reflected these rationalities. Over the turn of the millennium, rising oil prices led to energy security concerns in the global North, which provided context for two strategies with proposed co-benefits for addressing climate change as lower-carbon 'bridging' fuels. The first is biofuels: a sociotechnical strategy with multiple generations, each with unique characteristics. The 'first generation' of biofuels, generated from food crops, had for years been supported by US and EU policy (e.g. the EU's 2003 Biofuels Directive; the Energy Independence and Security Act of 2007 in the US) as a marrying of energy security and climate objectives. Uncommonly amongst the sociotechnical strategies assessed here, first generation biofuels in the mid-2000s represented an internationally scaled system of production and usage across the global North and South. But from 2007 to 2008, a global food crisis threw biofuels' conflicts with food security into sharp relief. A range of studies have since pointed out the effects of biofuels demand in moving production from traditionally food-growing areas into cash crops – although a number of factors, including escalating oil prices, acted in sum to generate food shortages (e.g. Naylor et al., 2007; Clapp & Cohen, 2009; Ajanovic, 2010).

Next generation biofuels – the second is based on non-food residues (prominently, cellulose), and further generations propose the use of algae and other materials – were then proposed to regain co-benefits across the 'biofuel trilemma' (Tilman et al., 2009; see also Hunsberger et al., 2014 on 'sustainable biofuels'). Despite tremendous hype, next generation biofuels remained commercially unscaled through the Copenhagen period, with the 2008 recession reducing incentives for bridging considerable technical gaps. Only towards the present day has some biorefinery infrastructure been approached and growth projected; though these remain far short of original targets (Hayes, 2013; Valvidia et al, 2016; Hassan et al., 2019).

The value of these proposed biofuels over the past decade has, arguably, been as a promissory 'bridge' not only for higher-carbon fossil fuels (e.g. in transport), but for locking-in the older, more controversial version of itself. The idea of 'next generations' was a proxy for an imagined biofuels industry evolved to link climate, energy, and food imperatives – and has thus maintained the political positioning, policy support, and infrastructure of first-generation biofuels precisely by claiming that they would inevitably be substituted (Kuchler, 2014).

4.4.5 Shale gas

Shale gas, emerging around 2008 in the US, was another form of 'bridging' fuel with co-benefits – we use shale as an imperfect proxy for debates on the potentials of other unconventional, 'tight' fuels. As with biofuels, shale gas was a beneficiary of US energy security goals; its potentials as a new fuel sector during the 2008 recession gave it further visibility. Combined with the refinement of hydraulic fracturing and horizontal drilling approaches, the expansion of shale gas operations in the US has been widely termed a 'revolution'. And like biofuels, shale gas was advertised for its climate co-benefits, a kind of 'green carbon' that would substitute for higher carbon options – in this case, coal in electricity generation (Tour et al., 2010; Howarth et al., 2011). This 'bridge' was premised on shale gas disrupting the political resonance and infrastructures of the coal industry, but analysts were wary that shale gas would substitute for renewables rather than coal in the near term, as well as generate lock-in around its own policy support, structures, and markets in the long term (Schrag, 2012; Levi, 2015).

There is mixed evidence about which kind of substitution is coming to pass. US emissions fell during the scaling up of the shale gas industry, but gas-for-coal substitution was only one contributing factor (Feng et al., 2015), and methane leakage in upstream processes remained an issue (Newell & Raimi, 2014). Without concerted policy 'guardrails' – for example, limiting energy demand growth, reducing methane leakage, ensuring substitution with coal rather than renewables, and restricting low-carbon lock-out (Lazarus et al., 2015; Shearer et al., 2014) – the lock-in of shale gas interests may in the long-run produce comparable climatic impacts to coal, due to a combination of 'fugitive' methane, effects on depressing oil prices, and expanding infrastructure (Waxman et al., 2020). Moreover, shale gas was in this period a US-centered enterprise. With large global reserves and growing markets in Asia and the EU, shale's implications in multiple issues – geopolitical, economic, in energy systems – are still unfolding, from which impetus for its development may ultimately lie (Holz et al. 2015).

4.4.6 Short-lived climate forcing pollutants

Around 2011, the debate on *short-lived climate forcing pollutants (SLCPs)* repurposed efforts to reduce a heterogeneous range of aerosols from industrial production, agriculture (crop degradation), and other sectors as a co-benefit between air pollution, ozone layer governance, health, food security, vulnerable populations, and climate change (UNEP/WMO, 2011; Shindell et al., 2012). Discussion on SLCPs within the UNFCCC COPs were muted during this period, but as early as 2012, a still-growing Climate and Clean Air Pollution (CCAC) of states, cities, and organizations was lauded as an example of climate governance's new polycentricism. Many saw an opportunity to sidestep the UNFCCC and to generate climate action at less fractious venues. SLCPs, indeed, saw rapid policy expansion at the international level, with the Gothenburg Protocol of the Convention for Long-range Transboundary Air Pollution taking on black carbon (BC) in 2012, the Montreal Protocol on ozone in 2016 addressing hydrofluorocarbons (HFCs), and the Arctic Council adopting BC targets in 2017.

Besides seeking co-benefits and spurring effective polycentrism, a key rationality underpinning SLCP actions was the capacity to reduce warming in the near-term (prior to 2050), since SLCPs remain in the atmosphere for a fraction of the time that carbon does, while in some cases embodying many times carbon's warming potential. Victor et al. (2015) argued that tangible, feasible action in the near term (recall conversations on CCS, biofuels, and shale oil) might spur heavy carbon emitters to take on more comprehensive actions in the future, and disregarded the prospect SLCPs might distract from long-term carbon reductions as a 'curious political logic that imagines countries can't focus on more than one thing at a time' (p.796).

Scientific networks, generally, were circumspect, warning that SLCP reductions could not buy time or provide a bridge for low-carbon transitions. SLCP reductions could slow certain near-term risks (e.g. some ecosystems; sea level rise), but would not halt warming in the long term if carbon was not also reduced. More plainly, SLCPs could not allowed to be fungible with or substitute for carbon, as this might disguise and prolong emissions of the latter (Myhre et. al., 2011; Bowerman et al., 2013; Shoemaker et al., 2013; Allen, 2015). Yet, some evidence indicates this is coming to pass in the post-Paris period, where Nationally Determined Contributions (NDC) include SLCPs under a single, economy-wide GHG metric, shading distinctions between actions on near-term SLCPs and long-term carbon in reaching their targets (Ross et al., 2018; Shindell et al., 2017).

4.4.7 Carbon dioxide removal

A final pair of sociotechnical strategies in this era emerged in the mid-2000s, originally grouped as forms of '*geoengineering*' or '*climate engineering*'. The term encompasses two technically dissimilar suites: carbon dioxide removal (CDR) proposes a variety of natural and technological sinks for filtering and storing carbon directly from the atmosphere (unlike CCS, which operates at source), while schemes for solar radiation management (SRM) propose that increasing the albedo of the planet's surfaces could reflect a degree of sunlight and thereby reduce warming and its impacts. The initial pairing of these suites was a function of scale and intent, with early conceptualizing of both CDR and SRM as transboundary, even planetary interventions in the climate system (Keith, 2000; Shepherd et al., 2009), with some harkening to Cold War era weather modifications (Fleming, 2009) or a renewed sense of stewardship as part of the 'Anthropocene' zeitgeist (Brand, 2009; see also Rockström et al., 2009).

CDR, or of late, *'negative emissions technologies (NETs)'*, had a more circuitous rise to prominence. An early-2000s variant, ocean iron fertilization (OIF), was scientifically discredited following initial promise. The upscaling of a technologically-grounded range of direct air capture (DAC) approaches remains held back in part by high energy requirements (Wilcox et al., 2017). The collective prospects of the idea of carbon removal were revived in 2013 by the inclusion of *bioenergy carbon capture and storage (BECCS)* – an immature CDR proposal with a single pilot demonstration – in the vast majority of the IPCC Fifth Assessment Report's emissions scenarios on which the Paris Agreement targets of 2C and 1.5C came to be based. This led to observations that the achievability of global climate targets was functionally propped up by a speculative technology and its underpinning assumptions (Anderson, 2015; Geden, 2016).

BECCS has since been argued to implicitly commit climate governance to 'the promise of negative emissions', reflecting the promissory nature of CDR as well as the evolving framings of scientific assessment (Beck & Mahony, 2018). As a discursive totem, CDR or NETs continues to expand, and has come to marshal carbon sinks with diverse backgrounds: from DAC, to BECCS, to forms of terrestrial CDR often recategorized from existing land-use and forestry management practices, to ocean-based approaches. Conversely, CCS debates are referencing CDR to regain visibility (Bui et al., 2018). CDR's original framing as large-scale 'climate engineering' or 'intervention' is dissipating; the suite is increasingly normalized as carbon sink-based mitigation, and given impetus by platforms that aim at carbon neutrality by 2050 (Geden et al., 2019).

Given CDR's growing profile, many called pragmatically for investment and incentivization (e.g. Lomax et al., 2015; Bellamy & Geden, 2019). Yet, BECCS in 2013 was (and remains) a projection of integrated assessment modeling (IAM) that calculates IPCC scenarios – BECCS was prominently featured in emissions projections because of model assumptions that it would become highly cost-effective post-2050. Moreover, BECCS is a chimera of biomass energy and CCS, two sociotechnical strategies with resilient controversies (Buck, 2016). Suggestions for improving BECCS' potentials rely on improvements to CCS infrastructures and a turn to next-generation biofuels to reduce land-use trade-offs – in this sense, BECCS is an imaginary that builds on the unfulfilled potential of previous ones (Markusson et al., 2018).

Despite these uncertainties, heavy BECCS deployment in modeling scenarios allows emissions to 'overshoot' in the near term before being sequestered later in the century – effectively, a time-buying scheme for climate policy created from modeling parameters (Anderson, 2015; Beck & Mahony, 2018; Markusson et al., 2018; Carton, 2019) that reflects 'a long history' of how carbon sinks have been historically discussed and branded. The degree to which other novel CDR approaches may reflect similar logics is underexamined. Indeed, BECCS and direct air capture (DAC) share some of 'the same technical, regulatory, and financing frameworks needed for CCS' (Haszeldine et al., 2018, p.16) – and by extension, some potentials for prolonging carbon infrastructures. McLaren et al. (2019) proposes policy guardrails against perverse incentives in enhanced oil recovery (recall CCS), industry calls for CDR to serve as a source of (tradable) carbon offsets (recall carbon sinks and market mechanisms), and a hay substitutability between conventional carbon reductions and negative emissions in setting targets (a similar concern exists for SLCPs).

4.4.8 Solar radiation management

For most of the Copenhagen era, the idea of *SRM as regional or planetary sunshades* drew greater and more fractious debate than CDR. A 2006 essay by Nobel laureate Paul Crutzen (of ozone layer governance) saw one SRM option as selectively allowing some increase of climate-cooling sulphate pollutants that are already by-products of shipping and industry – an uneasy trade-off between air pollution and climate goals (Crutzen, 2006). These early links with SLCPs would go dormant, with SLCP governance focusing on the co-benefits with reducing climate-heating pollutants. SRM schemes came to be dominated by more novel, earth systems modeling-driven scenarios for a layer of reflective (often, sulphate) particles in the upper atmosphere, dubbed stratospheric aerosol injection, or SAI (Irvine et al., 2016).

SRM became active as a fringe but forceful idea – even now, it has negligible mainstream political support, and scarcely any development or demonstration projects (Doughty, 2018) and engineering beyond proof-of-concept calculations (Smith &

Wagner, 2018). The perceived technical strength of SRM – using volcanic eruptions as a proxy – has been its potential to cool the climate within weeks or months (Crutzen, 2006). A ballooning amount of assessment pointed out that sunlight reflection, as modeled, could reduce warming and many attendant harms (Irvine et al., 2016) while presenting a systemic range of environmental and political challenges (Blackstock & Low, 2018 collects articles written 2012-2016). 'Cheap, fast, and imperfect' became a resonant shorthand particularly of SAI (Parson & Keith, 2013), as did a 'risk vs. risk' framing – SRM perhaps made sense only in comparison to the risks of poorly-mitigated climate change (Linner & Wibeck, 2015).

Scientific networks sounded many cautious notes. An early framing of SRM as an 'emergency' mechanism was warned against for scientific uncertainties and playing into the politics of panic (Markusson et al., 2014; Sillmann et al., 2015). Deployment schemes by coalitions were studied but warily regarded (e.g. Ricke, Moreno-Cruz & Caldeira, 2013), and an initial assessment focus on regulation of prospective deployment (Victor, 2008; Virgoe, 2009) pivoted to a more polycentric governance of research itself (Nicholson et al., 2018). The most prevalent defense of SRM potentials came to be (and still is) as a time-buying strategy (Neuber & Ott, 2020), underpinned by scenarios that model SAI's capacity to reduce a broad spectrum of climate harms, especially if coupled with strong mitigation (e.g. MacMartin et al., 2014). These conclusions were accompanied by appeals to SRM's capacity to blunt impacts for vulnerable populations (Horton & Keith, 2016), that SRM could spur stronger recognition of and action on conventional mitigation (Reynolds, 2014), and calls for more enabling, mission-oriented research programs (Victor et al., 2013; Keith, 2017). Others described these scenarios as the use of modeling parameters to create as rose-tinted a depiction of deployment as possible, questioning benefits for the vulnerable as well as the capacities of a certain kind of model (and scientist) to set the terms of debate (Stilgoe, 2015; Flegal & Gupta, 2018; McLaren, 2018) in critique that mirrors that of BECCS in integrated assessment models.

Much contention existed over SRM's potential – due particularly to the 'cheap, fast, and imperfect' trope' – to reduce incentives for comprehensively reforming the carbon economy, as both an idea and as a sustained deployment. Recognition of these potentials remain pragmatic and prevalent; since the debate's earliest days, researchers have issued warnings is that SRM only masks warming, and cannot substitute for carbon reductions. For some, this so-called 'moral hazard' is ambiguously systemic and therefore unhelpful (Hale, 2012); for others, it is overstated (Reynolds, 2014). Of late, critical geography has revived SRM and its moral hazard as exemplary of a carbon economy fix, 'buying time for market-driven [mitigation] policy and reducing near-term risk' (Surprise, 2019; Gunderson et al., 2019) with a comparable logic to that of CDR and CCS (Carton, 2019). More concrete readings see moral hazard as forms of 'substitution' or 'deterrence' in mitigation efforts grafted onto existing sociopolitical issues and policy platforms, for which pre-emptive policy guardrails must be constructed (Lin, 2013; McLaren, 2016).

Table 4.2 Sociotechnical strategies

Sociotechnical strategy	Arrival period & circumstances	Degree of scaling	Match with Kyoto and Copenhagen governmentalities
Flexible mechanisms	1997 Kyoto Protocol	Kyoto Protocol 'flexibility mechanisms'	• Ecological modernization: cost-effective, market facing climate governance based on offsets and credit trading
CCS	2006-2010 debate on CDM inclusion	Permitted in CDM in 2011 but never scaled	• Ecological modernization: carbon markets, prolonging carbon infrastructures • Relative gains: sustaining carbon markets • Time-buying for easing carbon transitions
REDD+	Negotiated between 2005-2013; preceded by forestry and land-use debate	Modest number of projects, remains a financing mechanism.	• Ecological modernization: carbon accounting and credit generation • Relative gains: financing for forest nations • Co-benefits: development, biodiversity
Next gen biofuels	After 2007 food crisis, built upon early 2000s 1st gen biofuels	Only first-generation (food crop-based) scaled	• Co-benefits: energy and climate goals; pivoted to reducing trade-offs with food security
Shale gas	2005-2011, driven by energy security and industry innovations	Rapidly expanded in US; markets and reserves mapped in EU and Asia	• Co-benefits: energy and climate goals • Time-buying for easing carbon transitions based on gas-for-coal substitutions, catalyze more deep-lying mitigation
SLCPs	2011 recognition of air pollutants as climate heaters	BC, HFCs and methane listed in various platforms, including Paris NDCs	• Co-benefits: air pollution, ozone layer governance, health, food security, development and vulnerable populations, • Time-buying: accompany and catalyze more deep-lying mitigation
CDR	Early 2000s, with ocean fertilization; 2013 with BECCS in AR5	Increasing attention as part of Paris targets, but unscaled	• Ecological modernization: carbon markets, prolonging carbon infrastructures • Time-buying for easing carbon transitions based near-term carbon emissions overshoot
SRM	2006 Crutzen essay on sulphate forcing	Nascent small-scale mechanics tests	• Time-buying for easing carbon transitions by dampening climate impacts particularly for vulnerable populations, catalyze more deep-lying mitigation

Column 1 names emerging sociotechnical strategies of the Copenhagen era (2005-2015). Column 2 describes the period of arrival, while column 3 describes the degree of infrastructure scaling. Column 4 notes how sociotechnical strategies reflected evolving governmentalities of the Kyoto and Copenhagen eras, including logics of lock-in and fixing.

4.5 Analysis: Governmentality patterns

We previously noted how Copenhagen era (2005-2015) climate strategies were framed, how they embodied evolving governmentalities, and how they were beginning to appear as practices that prolong the near-term stability of the carbon economy. Here, we draw more systematic insights. We observe distinct patterns in how these sociotechnical strategies referenced governance rationalities and engendered forms of fixing, and in how strategies built upon the rationalities and infrastructures of those that came before (see column 4 of Table 4.2, as well as Table 4.3). Markusson et al. (2017; 2018) describe the latter as 'defensive fixes' – a path dependency of techno-fixes.

We observe a transition and continuity, rather than a clean break, between governmentalities of the Kyoto (1997-2005) and Copenhagen (2005-2015) periods. Fledgling strategies entrenched the carbon economy and mode of climate governance dominant during the Kyoto period in three ways: generating carbon credits, repurposing existing carbon infrastructures, and capitalizing on energy security.

The first shows the resilience of the market-facing practices of 'ecological modernization'. CCS, REDD+, and to a less clear degree, CDR, arose as *carbon sinks linked to offsetting, accounting, and trading mechanisms* (Røttereng, 2018). CCS was included in the CDM; as was the grouping of 'afforestation and reforestation' that is an antecedent to REDD+, which follows a similar logic of generating emissions credits. Strategies also *maintained infrastructures of carbon fuel extraction and usage* more directly. Fuels comparatively lower in carbon content – biofuels and shale gas – were argued to be substitutable for higher carbon variants in ostensibly limited circumstances, but in the process presented opportunities for lengthening the use of existing carbon infrastructures (e.g. the promise of next generation biofuels prolonging first-generation use; shale gas substituting for renewables as much as for coal, and expanding the long-term oil and gas economy), and for co-optation by industrial interests. Many argue that that CCS and kinds of CDR (e.g. direct air capture), through deployment in enhanced oil recovery, are beginning to follow in these tracks (Markusson et al., 2017; McLaren, 2019; Carton, 2019). BECCS is exemplary of path dependencies, linked to biomass energy and CCS, and further on to the logics of marketized carbon sinks (Buck, 2016; Markusson et al. 2018). The third positions climate goals as a *co-benefit with the pressing demands of energy security* (particularly in the US) emerging over the early 2000s, with the clearest examples being biofuels and shale gas.

At the same time, the shape of Copenhagen-era strategies shows the marks of emerging regime fragmentation in the mid-2000. A loss of confidence in the UNFCCC's centralized, managerial mode of governance in the fractious post-Kyoto negotiations, and an ensuing openness towards a *polycentrism of seeking climate-related goals* through adjacent UN regimes, minilateral coalitions, and multilevel arrangements of states, municipalities, industries, and civic organizations, became the Copenhagen era's prevailing rationality. The need to keep the climate regime alive took form as a strengthening of rationalities for seeking relative gains, co-benefits, and bridging strategies, which trickled down into the appeals to viability and legitimacy made of new sociotechnical strategies. At the same time, rationalities of co-benefits and time-buying in particular presented opportunities for locking in carbon structures in less direct ways than entrenchment of cost- and market- friendly governance, or governance directly coupled to systems of carbon extraction and use.

References to *co-benefits for legitimizing climate strategies* with energy security (biofuels, shale gas) and development (the CDM) were joined by the linked issues of land-use, forestry, and agriculture (REDD+ and various kinds of terrestrial CDR), and air pollution (SLCPs and biofuels). Food security became significant – as a minimization of trade-offs – for hyping new biofuels after the 2007 food crisis; this issue was newly raised for BECCS as a combination of biomass energy and CCS systems. Mayrhofer and Gupta (2016) point out that the 'co-benefits' rationality's main potential is to incorporate climate objectives into more immediate processes of local and global governance. At the same time, there are dangers in treating climate goals as 'side effects of another goal that might be higher on the political agenda' (ibid, p.27). The perception and advocacy of a co-benefit can fade as contradictions surface during operationalization – REDD+ and development, or biofuels and food security, or shale gas and energy-related imperatives – and balancing interests between governance issues becomes subject to scientific uncertainties and political horse-trading. Indeed, a co-benefits agenda might also be understood partly as trying to reframe critiques of harmful side effects. In some cases, if the driving forces of a climate strategy come from rationales external to climate governance – for example, shale gas – 'co-benefits' actually disguises trade-offs.

Another manifestation of the regime's fragmentation was an *increased openness towards relative gains* in the negotiation agenda that might maintain some momentum at the UNFCCC. Though it stands outside the scope of our investigation, Khan and Roberts (2013) point out that adaptation funding received much needed support (at least on paper) under this rationale. Negotiations for REDD+ as a financing mechanism for forest nations (2005-2013), and including CCS in the CDM (2006-2010), similarly benefited in the post-Kyoto process. Dovetailing with these rationalities were resurgent appeals to demographics apart from governments and industry to sustain climate action – Bäckstrand & Lövbrand (2016) note that the visibility of civic and non-governmental organizations in this period rose as part of a move to polycentrism. Some of this manifested as appeals to the *welfare of 'most vulnerable'*: as presenting co-benefits (or at least minimizing trade-offs) with development (next-generation biofuels, REDD+, SLCPs), or for SRM, as a measure that might alleviate climate harms and buy time for developing adaptive capacities (Horton & Keith, 2016).

The emergence of the *'time-buying' or 'bridging'* rationality – easing the near-term strain for economies and societies on route to comprehensive low carbon transitions – came with many varieties, and displays the strongest potentials for lock-in. Some tied clearly into the cost-effective, market-facing climate governance of the Kyoto era. An ostensibly transitory low-for-high carbon fuel substitution (biofuels and shale) has been noted. CCS tied into the structures of tradable carbon credits, and was exemplary of the promise to ease transitions for carbon infrastructures; a logic expanded for CDR (e.g. BECCS) in permitting near-term 'overshoot' of emissions trajectories due to the promise that emitted carbon can be sequestered from the atmosphere in the future. SLCP reductions are projected to reduce certain near-term impacts, and SRM scenarios promise the same by slowing or halting temperature increase.

In debates that accompanied the growth of each of these proposals, scientific networks were careful to preface that none of these options can or should in the long run substitute for reducing emissions by replacing conventional fossil fuels. Advocates (for example, in CCS) extended the idea of a 'bridge' to argue that feasible compromises might catalyse more systematic reductions in the future (Bäckstrand et al., 2011); a variation of this for SRM argues that the prospect of a planetary sunshade might shock actors into stronger mitigation (Reynolds, 2014). Nevertheless, it is already clear that the bridging rationality presents opportunities for prolonging carbon structures. CCS has yet to be implemented at scale despite a decade and a half of investment and hype, indicating that its function is served as ambition signalling (Markusson et al., 2018), and Røttereng (2018) notes this for REDD+ as well. US shale gas production (and biofuels, though this is not a fossil fuel) was deployed more due to energy security and intraindustry innovation rather than for climate objectives, and already displays self-sustaining logics (Lazarus et al., 2015; Kuchler, 2014). SRM and SLCPs present perverse opportunities for climate ambition based on proxies for comprehensive carbon emissions reductions: (rates of) temperature increase for SRM, or a more feasibly manageable basket of GHGs (e.g. HFCs) in SLCPs. Many countries, for example, combine HFC and methane reductions with carbon reductions through an economy-wide emissions target in the Paris Agreement's Nationally Determined Contributions (Ross et al., 2018); others warn that fungibility must not be emerge between conventional carbon reductions and negative emissions (McLaren et al., 2019).

Table 4.3 Governmentality patterns

Kyoto era →	**Copenhagen era**	
Green governmentality **Ecological modernization**	**Polycentrism and fragmentation**	
Flexible mechanisms – carbon markets, Joint Implementation, Clean Development Mechanism (1997-2012 heyday).		Reduced activity (2012-)
	Credit generating carbon sinks (CCS and increasingly forms of CDR) Financing mechanism for less-developed countries (REDD+)	
Co-benefits: energy security		
	Food security (next generation biofuels)	
		Air pollution (SLCPs)
	Relative gains	
	Co-benefits with development for most vulnerable (REDD+, biofuels, SLCPs) Funding (REDD+) or protecting vulnerable populations (SRM)	
Buying time / Bridging		
Substitution of lower-carbon fuels for high carbon variants (shale, biofuels)		
	CCS and CDR in enhanced oil recovery Claiming to catalyze future mitigation instead of de-incentivizing it (CCS, CDR, SRM)	
		Substituting for long-term carbon emissions with a different emissions basket (SLCPs) or a proxy measure of harm (SRM) Overshoot of near-term carbon emissions (CDR; functionally, SLCPs)

We show the emergence or consolidation of governance rationalities and strategies of the Kyoto and Copenhagen eras (bolded script, dark grey), alongside variations of those rationalities (light grey) as they emerged with various sociotechnical strategies.

4.6 Conclusion

A bird's eye view reveals what smaller scale analyses might not. Most studies of climate's sociotechnical strategies are based on single examples or smaller groupings, and when linking these systems, qualifications abound at eye-level. But taken as a whole, patterns emerge. The Copenhagen era's proposals and systems navigated emerging rationalities that responded to the increasing fragmentation of the global regime. However, they strongly reproduced entrenched structures and rationalities of the Kyoto era, presenting numerous outlets for signalling climate ambition while delaying more deep-lying forms of decarbonization.

Our intent is not to denigrate considerable advances that have been made in mitigation efforts, nor to declare all incoming climate strategy hopelessly compromised.

Indeed, we leave out a number of sociotechnical strategies from our assessment, particularly renewable energy and efficiency, nuclear energy, and adaptation strategies. When assessing how the near-term carbon economy is 'fixed' by emerging efforts, omitted systems may offer countering logics. Rather, we sound a cautionary note about hype and advocacy regarding immature and imagined sociotechnical strategies. From CCS to SRM, each debate in the course of emergence saw myopic claims made about that system's potentials, and even that they present opportunities for avoiding or altering conditions that hampered previous efforts. A longer and wider arc of climate governance – even limited to the decade between 2005 and 2015 – indicates that these proposals, for all their different technical specifications, filed into comparable and often well-worn political usages. Structure – governmentalities built around the carbon economy – does matter.

Yet, structure need not be deterministic. Pointing to these governmentalities has been accompanied by avenues for altering them, in the form of proposed policy incentives and safeguards – see Chhatre et al. (2012) for REDD+, Lazarus et al., (2015) for shale gas, Shindell et al. (2017) for SLCPs, McLaren et al. (2019) for CDR, and McLaren (2016) and Reynolds (2019) for SRM. The question is whether these guardrails can be constructed, as we move into a period of governance marked by the implementation of the Paris Agreement, spurred further by carbon neutrality platforms, the European Green Deal, and of late, the opportunities and constraints set in motion by plans to restart the global economy in the aftermath of Covid-19. Whether these sociotechnical strategies come to 'repackage' Copenhagen governmentalities in a laissez-faire mode of climate polycentrism (Bernstein et al., 2010; Held & Roger, 2018; Ciplet & Roberts, 2017; Blum & Lövbrand, 2019) or offer opportunities for catalyzing a low-carbon transition, depends on our collective determination that the past assessed here need not be prologue.

Chapter 5

Is Bio-energy Carbon Capture and Storage 'Feasible'? The contested authority of integrated assessment modeling

How are novel energy, technology, and land-use systems strategies for limiting climate change judged to be 'feasible'? Controversy has arisen around the research community behind integrated assessment modeling (IAM) scenarios used in the Assessment Reports of the Intergovernmental Panel on Climate Change. This regards the role played by an unproven component in projected energy systems—a coupling of bioenergy generation with carbon capture and storage techniques—that allow IAMs to achieve ambitious temperature targets since adopted by the Paris Agreement. To understand the unfolding effects of this 'back-stop' in climate research and governance, we engage modelers and critical experts to interrogate how novel technologies are assessed by and constructed within modeling, and how the kind of expertise—and by extension, the authority—held by the IAM community is being challenged. We find that the IAM community and its critics disagree fundamentally on how to produce, validate, and communicate expert judgments regarding energy futures, and that their argumentation strategies both reflect and reinforce different understandings of the proper relationship between scientists and policy-makers. We ask what these competing claims signal for future activity in this space, and conclude with a call for 'reflexive' modeling approaches to bridge perspectives.

Published as: Low, S. and Schäfer, S. (2020). Is Bio-energy CCS Feasible? The contested authority of integrated assessment modeling. *Energy Research & Social Science* 20, 101326.

- Low: Conceptualization; data curation; formal analysis; writing-original draft; writing-review and editing.
- Schäfer: Writing-review and editing

5.1 Introduction

If there is a narrative at the heart of climate policy, it is this: 'It is five minutes to midnight, but we can still make it, if we start to act now' (Geden, 2018). The pairing of urgency and feasibility around the reform of energy systems and the achievability of a livable climate—of the threat of disaster and the promise of avoiding it—keeps climate change politics as currently practiced alive.

The 'feasibility' component of this narrative—that 'we can still make it'—is functionally backed by key pathways of mitigation strategy featured in the resonant Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). These scenarios, tackling the difficult and acute question of future energy, technology, and land-use systems, are the efforts of an expert community built around integrated assessment modeling (IAM). Over the last decade, IAM expertise has become authoritative in IPCC mappings of options for achieving (or avoiding) future climates (Cointe et al., 2020). By extension, the ability of their work to mark the terrain between today's carbon economy and ambitious temperature targets as 'feasible' provides an important degree of scientific upholstering for climate policy.

One approach whose scope has been rapidly expanded consists of 'negative emissions technologies', or NETs: programming into models the assumption that increasing amounts of carbon can be removed from the atmosphere through the innovative expansion of carbon sinks. One particular approach—a coupling of bioenergy generation with carbon capture and storage, or BECCS—is currently attractive within modeling parameters because it simultaneously does two things that models seek to optimize: generate energy and reduce CO2 concentrations. Its large-scale deployment features prominently in scenarios simulating temperature rises of no more than 2 °C, underpinning the Paris Agreement's targets (IPCC, 2014; IPCC, 2018).

Yet, for all its prominence in modeling, BECCS exists only at the pilot stage; like all novel NETs, it requires the bridging of considerable technical and societal uncertainties in order to be deployed at the envisioned scale. BECCS' seeming appearance as a stop-gap towards otherwise improbable climate targets has provoked vigorous criticism in academic channels: not only regarding barriers to implementation, but on the uses and limits of IAMs, the roles of research communities built around them, and efforts of the IPCC to navigate the politics of climate assessment (e.g. Geden & Beck, 2014; Anderson, 2015; Anderson & Peters, 2016; Geden, 2016; Beck & Mahony, 2018). Yet, critique only illuminates part of the picture. Members of the IAM community argue that they have consistently warned about excessive reliance upon these approaches, while pointing out uncertainties and research agendas (van Vuuren et al., 2011; Tavoni & Socolow, 2013; Fuss et al., 2014; Smith et al., 2016; Minx et al., 2018; Fuss et al., 2018).

Following scholarship in science and technology studies (STS), we see these exchanges as an example of 'controversy', in which differing values, forms of expertise, and understandings of how science and policy should relate to each other become visible when intra-scientific processes are exposed to criticism (Jasanoff, 2012). To access these understandings, our study inquires after the lodestone of that controversy: how the 'feasibility' of BECCS is understood, calculated, and communicated. Why does this matter? 'Feasibility' is an amorphous concept that allows for interpretations amenable to different demands. We find that judgments of BECCS's feasibility are proxies for wider worldviews, tied up with different understandings of the freedom of scientific inquiry in policy-driven assessments, the proper relationship between science and policy, and the shape of science communication. In turn, these understandings underpin different ideas for the reform of IAM assessments, with repercussions for how future mitigation strategies will be mapped—and perhaps, executed.

Section 5.2 introduces critical literatures in which our analysis is grounded. Section 5.3 explains our research method, in which we map the argumentation strategies of members of IAM groups involved in the construction of BECCS-heavy pathways, and contrast their responses with those of an interdisciplinary grouping of experts critical about the role of IAM activity in recent climate assessment. Section 5.4 presents our interview results, revealing diverging understandings of BECCS' feasibility and the scope of IAM work. Section 5.5 explores how feasibility judgments are co-produced with longer-running perspectives on the proper relationship between science and policy in (climate) governance, and question what implications they hold for future research and policy. Section 5.6 concludes with reflections on attempts to put perspectives into conversation, with an eye to process reform, in future modeling.

5.2 Literature and theory

In climate governance, where data on an unformed future is produced through simulations of climatic and societal trends, modeling constitutes a legitimized form of speculative research. IAMs are heterogeneous assemblages of climate, land-use, economic, and energy systems models that underpin Working Group III assessments of mitigation options (Beck & Krueger, 2016). Since 2006 (for eventual incorporation into AR5), IAM work has undergone a community-wide shift to a 'matrix architecture', where scenarios are developed by varying three kinds of parameters: radiative forcing, socioeconomic development, and policy. The first is covered by the Representative Concentration Pathways or RCPs; for this study's purposes, the RCPs constitute the only relevant framework, as they house the results included in AR5's assessment of mitigation pathways.[6] Scenarios within the RCP framework calculate emissions trajectories that correspond to ranges of radiative forcing (or likely temperature increase) in 2100 (van Vuuren et al., 2014). Depending on the 'target' posed, these emissions pathways implicate profound changes in technological and societal systems (the mitigation options), of which BECCS deployment is only one example (IPCC, 2014).

Our study joins a growing literature that acts both as a post-mortem on the appearance of BECCS in IAMs and as a prospectus for the use of IAMs in the future, encompassing a number of dimensions. The technical opacity of the internal structure of IAMs, as well as their imperfections as a platform for climate policy, are historically well-documented criticisms in economic modeling literature; Gambhir et al. (2019) reviews such critique through the lens of BECCS. Our work leverages studies grounded in critical social sciences. Recent works, for example, reflect upon policy narratives

[6] This nuance is not trivial. The matrix architecture that appears to have prioritized the RCPs also includes two other parameter frameworks: the Shared Socioeconomic Pathways or SSPs (which vary societal and political landscapes) and the Shared Policy Assumptions or SPAs (which vary policy configurations). The RCP scenarios were intended to be cross-referenced with the societal and policy dimensions of the SSPs and SPAs to form more well-rounded scenarios – but crucially, the latter frameworks had not been fully developed in time for inclusion in AR5 (around 2013), and are now coming fully into play as bounding parameters for IAM work. For a rapidly proliferating range of SSP-informed scenarios, see the database at http://www.iconics-ssp.org

embedded in scenarios (Beck, 2018) and the value judgements buried in ostensibly technical modeling choices (Ellenbeck & Lilliestam, 2019). Ethnographic studies of IAM-deploying institutions are growing. Hughes and Paterson (2017) highlight an elite cluster of economist-heavy research groups based in the global North, while Cointe et al. (2020) trace the emergence of the IAM community itself—in particular, the 'repertoire' of projects, procedures and philosophies that now underpin its authority within the IPCC. Further analogues emerge in the wider modeling ecosystem. Beck and Krueger (2016) and Hulme and Mahony (2010) document lively exchanges between climate modelers and their critics on the political dimensions of climate models: the agendas and responsibilities of modelers in shaping simplified but resonant depictions of future climatic impacts, while under pressure from supposed policy imperatives, funding incentives, and disciplinary demands.

Rather than map the landscape of IAM research groups and users, our study maps perspectives that marshal the efforts of modelers and critics. Haikola et al. (2018) represents a recent example; unlike this study, we focus on boundary work (Gieryn, 1983) and boundary objects (Star & Griesemer, 1989) as an explanatory framework for the contestations witnessed in participants' attempts to navigate and resolve controversy. Boundary objects—an iconic example in the modeling space is the definition of 'uncertainty' in GCMs, in Shackley and Wynne (1996)—act as a discursive totem around which (expert) communities can engage. At the same time, stakeholders advance their separate areas of authority by defining the objects and terms of debate in ways responsive to their own expertise and agendas—this is boundary work.

Branches of STS have theorized how scientific controversies are navigated in varying, intersecting ways—for example, as a competition of 'interpretive flexibility' over facts ('social construction of technology', Bijker et al. 1987), or the coming together of things, ideas, and people in relationships ('actor network theory', Callon, 1986). We reference the 'co-production' framework of Jasanoff (1990; 2004), which defines boundary work as contestations over scientific knowledge and its appropriate relationship to policy that reflect and reinforce different conceptions of social order. Following a co-productionist perspective on boundary work allows us to reach beyond intra-scientific processes of social construction or network-building, and to understand controversies as revolving around competing political worlds that contain distinct representations of the role of scientific inquiry in society. Leveraging these literatures, we apply the concepts of boundary work and objects to 'feasibility' as an entry point to understanding how the authority of IAM-based definitions and forms of expertise are contested.

5.3 Methods

13 participants (anonymized, Table 5.1) were chosen according to three criteria: a roughly even divide between modeling and other disciplinary backgrounds, inclusion of senior figures in the IAM community, and demonstrated engagement with the emergence of BECCS in IAMs. It was not our intention to create a 'mini-public', or to comprehensively map disciplinary perspectives. Rather, we chose to capture controversy at a moment in time amongst a cohort of engaged actors.

We categorized participants into four groups: (1) four self-identified members of the integrated assessment modeling community (IAMs), (2) four with varying modeling backgrounds, who have worked with but do not identify as part of the IAM community

(Models), (3) two from science and technology studies (STS), and (4) three in global climate policy (Policy).

Our process consisted of two rounds of engagement. The first was an online survey (Round 1) to which participants typically gave paragraph-length answers.[7] Following the principle of inter-rater reliability, the authors assessed the answers for themes that reflected agreement or contention. Care was taken to see if themes could be identified along disciplinary lines, and particularly ones demarcating understandings between modelers and critics of BECCS in IAM work; as well as co-occurrences between themes that might indicate larger constructs of reasoning. This was followed by individually conducted, semi-structured interviews (Round 2) that honed in upon themes established in Round 1. The refined themes of the Round 2 interviews form the results presented in Section 4.

Finally, a note on positionality. The authors come from an STS background, as do many observers critical of BECCS in IAM scenarios. The reader will note that a sensibility grounded therein informs our analysis, but we hope that this will not be misread as unsympathetic to IAM work. Our intent is to map the arguments of defenders and detractors with equal focus, and to understand diverging perspectives with an eye to bridging them.

5.4 Results

Six themes emerge—we list these below as question sets. They reflect areas of inquiry fleshed out in conversation, rather than exact phrasings posed to participants.

(A) How should the feasibility of BECCS—or novel technologies in general—be defined or calculated?

(B) What constraints or incentives shape researchers' agency when asked to investigate pathways towards ambitious climate targets (2 °C and 1.5 °C)?

(C) Do the results of modeled pathways present options for achieving various climate targets neutrally, or make certain strategies appear more necessary than others? Where do responsibilities lie in applying results?

(D) How does the IAM community communicate on or provide access modeling processes and results, and how are these efforts understood by themselves or other actors?

(E) What would researchers describe as constructive critique of IAM processes and results?

(F) What concrete reforms should be made to the processes by and contexts within which IAMs operate?

These themes serve as anchor points along which argumentation diverges, reflecting differing epistemologies and agendas. But while the construction of feasibility anchors our inquiry, it cannot be the sole focus. Rather, what one thinks of feasibility reflects different ways of thinking about process, authority and science-policy interactions, as represented in the other themes. This is the essence of boundary work, and the subject of more detailed discussion further on.

To explore these, we must begin in section 5.4.1 with the 'feasibility' of BECCS, for which no clear, multidisciplinary consensus could be found, and to which only a

[7] The survey from Round 1 can be accessed at: goo.gl/F1KZBb

technical definition could provide a common basis for conversation. The credibility of the technical definition, then, comes attached with understandings that diverge imperfectly along disciplinary lines in two rough blocks, and demarcate competing judgments on the value of IAM expertise for providing a base of knowledge in climate strategy.

The first block is coherently driven by the understandings of participants from IAM groups—we label this an *'incumbent'* perspective (section 5.4.2). Responses that reflect a critical analysis of certain aspects of IAM work are characteristic of the second block, supported by a more interdisciplinary spread of participants with backgrounds in different kinds of modeling, STS, and policy—this, we label a *'critical'* perspective (section 5.4.3). We present these views in a form that walks the line between data and narrative, and even where they are presented in the rhetorical form of factual statements, they should be read as representing the positionality of the interviewees. However, the juxtaposed perspectives should not imply that participants can be sorted without nuance into 'for' and 'against' camps—the reader can consult Tables 5.2 and 5.3 following the main text to note the diversity of participants speaking to each theme or component position.

5.4.1 The technical definition of feasibility

All participants agreed to engage with the IAM community's technical definition: Feasibility is a function of model solvability. The concept can be applied either to the technologies that exist as options for modeling pathways to particular temperature targets, or to the scenarios laying out pathways of deployment. However, feasibility is only indirectly calculated: groups operating particular models pose constraints upon technological options or scenarios, which determines whether, and in what amount, a technology emerges. The focus is on technical and economic dimensions, and social and political aspects are not explicitly considered (see footnote i). The shape of constraints relies upon the judgment of contributing experts, and processes vary with regard to different technologies. IAMs are often 'optimization' models, calculating the most efficient pathway(s) towards particular temperature targets. If a model—given aforementioned constraints—cannot 'solve' for a target, that result goes unreported (Tavoni & Tol, 2010).

In sum: what is 'feasible' is *de facto* what is computationally possible, given initial constraints that are based on interdisciplinary and not uniformly codified expert judgments, and that change from model to model. A scenario is feasible if the model can solve for a temperature target, and a technology is feasible if it was made available as an option at all. Scenarios that are highly implausible in reality, or that produce alternative pathways to the same goal, are all technically feasible.

5.4.2 A modeling-based 'incumbent' perspective

A. Feasibility is contained within the reality of modeling: For many with (integrated assessment) modeling backgrounds, the large-scale inclusion of BECCS in ambitious pathways is justifiable because IAM work does not seek to produce direct representations of reality. IAM participants spoke of having two notions of feasibility: the technical version that is part of their shared professional equipment, and a second that appears more personally defined by intuition and experience with climate policy.

And while most admitted to personal misgivings about BECCS, or certain scenarios, or climate targets, all emphasized the professional definition when confronted with criticism (e.g. that the 2 °C target is functionally supported by BECCS). Modelers labeled IAM work as an 'explorative' space for mapping alternative mitigation strategies at a systemic level, under experimental assumptions. Modeling constraints are malleable and can produce unintuitive outcomes, but 'outliers' are contextualized within a wider range of results from multiple models, targets, options, and assumptions to guard against arbitrariness—this is the logic of model inter-comparisons, which underpin the production of all IPCC pathways. Nor is the internal complexity of IAM work prohibitive. Models must navigate a tension between usability (which calls for simplicity) and reflection of reality (which calls for complexity); moreover, complexity is supposed to produce emergent insights—simplistic calculations would not require models. Finally, many modelers pointed out that all emissions reductions measures—any number of fledgling sociotechnical systems—have to be triggered to their full potential to achieve ambitious emissions pathways, and BECCS is being unfairly singled out by critics.

B. Agency is the duty to assess policy options and targets by scientific standards: Underpinning this depiction of IAM work as 'explorative' is the perception that responsibility for determining climate targets or using scenario insights for policy is a matter for decision-makers and society, not the IAM community. Novel options (e.g. BECCS) or targets (2 °C or 1.5 °C) have to be 'taken as given' and cannot be prejudged without assessment; personal intuitions about feasibility or desirability are irrelevant. Potential misuse should not deter explorative research, but be prevented or preempted by increasing basic literacy in modeling intents and limitations amongst those who might use its results.

C. Modeling maps the solutions space: Accordingly, IAM participants emphasized the advisory, 'map-making' function of their work: scenarios provide decision-making support, and are neither predictions of the future nor prescriptions for a particular climate target or raft of mitigation measures. Many referenced the 'policy relevant but not policy prescriptive' mission statement of the IPCC. Some pointed out that scenarios exercise no discernable influence in propping up ambitious climate targets or driving a rush towards BECCS development, and that optimal pathways have historically failed to inspire the scale of mitigation efforts that they model. IAM participants also argued that policymakers are capable of understanding the complexities of scenario construction, and that senior modelers are aware of the contexts surrounding policymakers.

D. Communication requires improved model and scenario documentation: Given skepticism that IAM work has inherent potential for self-fulfilling prophecies, many with modeling backgrounds expressed confusion regarding criticisms of the IAM community's outreach and openness, which they judge is being conducted to a reasonable, if improvable, degree. Scenarios are made available in databases (IIASA, n.d.; ICONICS, n.d.); modelers are improving model documentation (e.g. IAMC, n.d.; ADVANCE, n.d.) and collaboration to improve basic literacy in IAMs (e.g. SENSES n.d.; DIPOL, n.d). Modelers admitted that co-authorship is a standard request made of those who use code and data, but this is not gate-keeping—some quality control is needed to navigate the trade-off between external verification and misuse for perverse scientific and political positioning.

E. Critics misunderstand 'explorative' IAM work: These reasonings coalesced revealingly when IAM participants addressed what they saw as the major misconceptions that critics had about their work, and as the objectives of useful critique. Modelers were eager to clarify two perceived misconceptions: firstly, that the IAM community prescribes the eventual deployment of BECCS or negative emissions; secondly, that IAM work is predictive rather than explorative. Present critique unfairly implies a disproportionate burden on the IAM community, and other disciplinary communities seeking to be valuable should help broaden understanding of the barriers to BECCS rollout, or explore the consequences of and alternatives to not deploying BECCS.

F. Reform as 'reality checks' and scenario diversity: IAM participants were receptive to exploring new metrics and common languages for feasibility, citing that 'reality checks' with industry professionals, ecosystems scientists, and social scientists should be expanded, and applied not only to assessment of scenarios, but to assumptions that shape scenarios. At the same time, some IAM participants emphasized the merits of a bounded, technical definition of feasibility fit to modeling purposes, warning that efforts to expand the definition and the objects of inquiry, while worthwhile, could result in nebulousness and inapplicability. Greater scenario diversity was also cited as necessary, highlighting societal values, technological options, and policy configurations that move beyond the current depiction of BECCS as a stop-gap. For many with modeling backgrounds, these efforts would serve to improve calculations of feasibility, underpinned by the collective value of scenario ranges and model inter-comparison for increasing confidence in results. Finally, enhancing engagement was considered necessary, with many calling for new incentive structures that prioritize wider consultations and interdisciplinary collaboration, and highlighting in particular the role of funding bodies. Time and resource constraints in the transitions between IPCC Assessment Reports—particularly between AR5 and the Special Report on 1.5 °C—were also mentioned as obstacles; here, the IPCC was called upon to mandate and convene spaces for reform. IAM participants emphasized that policymakers have strong responsibilities regarding these spaces of exchange, reasoning that stronger modeling literacy amongst climate delegates allows an appropriate division of labor between science (informing options) and policy (setting objectives, and executing options).

5.4.3 An interdisciplinary 'critical' perspective

A. Feasibility is undefinable, but requires a stronger fidelity to reality: From critical viewpoints, the technical judgment of BECCS' feasibility influences political perceptions of the 2 °C target's feasibility. When asked to provide an alternative definition of 'feasibility' to that of the IAM community, critics implicitly conflated it with 'reality'—but otherwise struggled to define either concept or the relationship between them. Some mentioned biophysical, technical, and sociopolitical dimensions of feasibility by turns; others named adjoining concepts of robustness, credibility, or legitimacy of evidence, referencing the 'confidence statements' used in IPCC Assessment Reports (Mastrandrea et al., 2011). But critics tended to bracket the definitional issue, focusing instead upon the implications of logics based in modeling practice for political actions in reality. Some highlighted the malleability of model inputs as problematic—overly optimistic assumptions can result in fledgling technological systems acting functionally as backstops for reaching targets, with the heavy presence of nuclear technology in earlier scenarios raised as an analogy (Keepin & Wynne, 1984). Others noted that 'outlier' results can be used as 'silver bullets': in this case, scenarios that present perceived possibilities for maintaining the carbon economy will be inevitably adopted by opportunistic actors. The internal complexity of IAMs, moreover, makes it difficult to trace the calculations of those outcomes. Finally, inter-comparisons do not necessarily keep the modeling enterprise honest; rather, they often harmonize (unfeasible) assumptions across models.

B. Agency is the responsibility to take the politics of scientific assessment seriously: Many critics argued that 'taking policy as given' therefore reflects a false objectivity. Research is a choice; there has to be responsibility in gauging one's political impacts. Claiming a neutral stance towards novel areas of research, or that results are conditional upon model, scenario and assumptions, simply allows the IAM community to distance themselves from their own choices, and by extension, from criticism. Some speculated on motivations, constraints, and incentives: privileged authority in the present structure of IPCC assessments (where IAM networks form the backbone of Working Group III), or funding and publication opportunities presented by emerging areas for model application, or the tribalism of disciplinary communities, that prioritize further model application ahead of more fundamental reforms of model structure. Critics from policy and STS backgrounds tended to note that policy objectives increasingly drive, structure, and evaluate climate assessments. For example, in the current mode of IPCC work, modelers are asked to generate pathways towards politically negotiated targets (an example of 'regulatory' science, see Jasanoff, 1990).

C. Modeling shapes the solutions space: Whatever their intent, scenarios contain signals and have functional effects. Research does not simply 'map'; it actively adjudicates between options by creating criteria and storylines on their benefits and risks (a potential also highlighted by IAM participants). STS-grounded participants, in particular, described BECCS-heavy scenarios as 'performative', with others joining them in arguing that these functionally prop up the viability of ambitious temperature targets and heighten the potential for the hijacking of BECCS (as a silver bullet) by actors beholden to the carbon economy. Policy-grounded critics argued that IAM community does not adequately grasp the perversities of politics. The promise of eventual carbon removal may allow policymakers to placate competing constituencies—strong climate targets satisfy greens, while continued carbon dependence satisfies certain economic interests. Alternatively, decision-makers want to appear informed, and generating this impression requires funding research whose results are largely cosmetic. And with key exceptions, modelers (or researchers in general) were argued to be driven more by curiosity than how research is subject to political context and messaging.

D. Communication requires interrogation of IAM practice, not only results: Given the potential of explorative research being politicized to drive perverse outcomes, and the seeming lack of awareness to this danger, critics expressed dissatisfaction with what they saw as the IAM community's technocratic, insular nature and routine efforts at outreach. The availability of scenario results, highlighted by the IAM community as an example of openness, was argued to be trivial if processes—model structure, and the internal workings of the community—remain closed. Some critics also speculated that members of the IAM community communicate different messages (regarding the feasibility of BECCS, or IAM practices) to different constituencies, with seeming intent to maintain the coherence of their community in the face of external criticism. Critical commentary on IAM practice, then, reflects efforts to open up the 'black box'.

E. Modelers misunderstand critique: Critics claimed to understand that IAMs are intended to be explorative, and that BECCS is not an intentional political agenda, but a model-derived stopgap. The IAM community, rather, misunderstood a subtler set of observations—that modeling BECCS circuitously allows the IAM community to reap the rewards of policy-relevant work, that there is inadequate feedback from users of modeling results in modeling processes, that there are dangers of a purely enabling stance towards BECCS research, and that choices made by researchers can have prescriptive effects for politics where there is a close coupling between policy-making and scientific advice—here, through IPCC Working Group III activity. At the same time, most critics admitted that their efforts were 'big picture' analyses that did not truly penetrate the internal politics of IAM research groups, and some mentioned comparisons to the structure of the climate modeling community as an analogous entry point.

F. Reform as addressing equity and structural change: Critics suggested corrective measures comparable to those suggested by IAM participants such as new metrics for feasibility, greater scenario diversity, and more innovative engagement and transparency—but with different emphases. The technical definition of feasibility was repeatedly highlighted as inadequate for grappling with its unintended political consequences, but critics understood reform in more diverse ways. Most emphasized the need to source new technological, ecological and political dimensions of feasibility to improve modeling design as a first step; others also saw improving feasibility as part of a larger reevaluation of the IAM mode of modeling-for-targets. A more plural spread of scenarios and pathways was phrased as 'extended peer review', underpinned by the need to make explicit the performative influences of IAM work. And while IAM participants noted the role of decision-makers in increasing transparency, for some critics, it is the IAM community who must grapple with a disproportionate influence in framing the viability of novel options and climate targets, and should take the appropriate responsibility for communicating modeling practice through measures more innovative than peer-reviewed publications, model documentation, or conventional policy outreach.

5.5 Analysis: Defining 'feasibility' reflects boundary work

The exchanges above represent boundary work, in which contestations over an ostensibly common frame of reference—in this case, 'feasibility'—are co-produced with diverging understandings of what is, and what ought to be, the proper relationship between science and policy. In less disciplinary terms: When defining feasibility, actors are speaking to what they see as the proper relationship between modeling and climate policy in particular, and science and society writ large. From this, their arguments establish competing depictions of the authority—some arguable capacity to set certain terms of debate—that IAM expertise wields in IPCC assessments, and the propriety of that authority.

Let us begin with the 'feasibility' of BECCS. Most participants share a personal sense that BECCS, as modeled, is questionable—there is some misalignment with BECCS' assumptions, scales, and timelines, and what the participant believes about the real world. But adherents to the 'incumbent' perspective emphasize the definition most amenable to modeling practice: Model solvability, with alternative depictions of the techno-economic and biophysical requirements and implications of roll-out at scale. Modelers phrase the improvement of feasibility as a 'reality check', in which technical (and to a lesser degree, sociopolitical) uncertainties can be fleshed out by adding dimensions to the barriers and implications of deployment. This attempt to align 'feasibility within models' and 'feasibility in reality' represents a well-worn debate within IAM practice (Haikola et al., 2018; Gambhir et al., 2019), and only relates to mitigation options and scenarios. The critical perspective, however, stretches the IAM community's coverage of feasibility to include (however inadvertently) key climate targets. If BECCS is judged feasible by way of inclusion in 2 °C and 1.5 °C pathways (however BECCS is qualified and bracketed technically), then the IAM community has contributed to a depiction of those temperature targets as feasible.

Defining what feasibility can be applied to (e.g. BECCS, wider mitigation strategies, or climate targets) and how it can be calculated (via the methods of integrated assessment modeling or by other methods), comes about as part of establishing what IAM expertise speaks to, and should speak to. This is the 'boundary': the demarcation between what matters for modeling in IPCC assessments, and for science in policy, that establishes where researchers are responsible—as well as what lies outside of their purview and influence, where failures do not erode their authority. Following Sundqvist et al. (2018), this boundary is fundamentally a demarcation between the (albeit idealized) worlds of science and politics, in which judgments on the proper shape of scientific advice depend on how one observes—and secondly, desires—a stronger separation or entwining of those worlds (see also Turnhout et al., 2013). IAM argumentation proposes a division of labor between IAM mappings (i.e. science) and climate targets and strategies (i.e. policy and politics). Critics attempt to dissolve the boundary; to introduce secondary, external repercussions into the purview of IAM work by highlighting the inevitably political nature of scientific policy advice. These efforts can be seen in several areas.

The first regards the freedom of inquiry and its relation to responsibility in policy-relevant science. Critics question whether the centrality of the IAM community to the IPCC's mappings of mitigation options constrains their research questions, such as taking 2 °C and 1.5 °C as targets for pathway modeling, and in a more circuitous way, led to the emergence of BECCS. Indeed, some critics harken to what STS refers to as 'regulatory' or 'mandated' science, where scientific work is structured by relationships, and even quid pro quos, with policy (Gieryn, 1983; Jasanoff, 1990). Critics, then, call for discretion—framed as 'choice' or 'responsibility'—in the conduct of IAM work. Many of modeling backgrounds, rather, rejoin that science is defined by the very absence of personal politics. These, then, are competing attempts to define elements of responsible research. For critics, it is the agency to question the propriety of research; for most modelers, it is the duty to conduct and evaluate that research by disciplinary standards, regardless of political premise. The modelers' view, by extension, highlights that responsibility is more properly defined by the use (rather than conduct) of research, and crucially, this lies outside of the purview and control of scientists.

A second area is the implications of modeling results on climate policy, touching upon what STS literatures refer to as 'performativity'—things, by way of existence, have effects. Critics argue that BECCS has set numerous effects in play: the stabilization of 2 °C and 1.5 °C ambitions in climate governance, the normalization of BECCS or some alternative form of carbon removal, and the crowding out of alternative mitigation and adaptation strategies (for further context external to our study, see Beck & Mahony, 2018; Haikola, Hansson & Anshelm, 2019). IAM and modeling participants, in response, invoke the 'policy relevant but not policy prescriptive' IPCC mandate, and emphasize that the intent of IAM work is 'neutral mapping'. A smaller number of modelers acknowledge that IAM work can have effects incongruous to intent. But they also help demarcate a safe space for modeling by questioning if 'performativity' is too general a concept to be helpful to scientific practice, and is best left to the communication of research results rather than interrogating the conduct of research itself.

A third area revolves around the appropriate shape of critique. Critics attempt to shift the terms of debate to the politicization of science though references grounded in critical social sciences: for example, 'regulatory science', 'external peer review', organizational theory on the calculus of policy makers (e.g. Cohen et al., 1972), ethnographies of climate modeling groups as a template for the IAM community (e.g. Shackley & Wynne, 1996), and the heavy deployment of nuclear power in previous IAM work as an analogue for BECCS's role as a model-derived stop-gap (e.g. Keepin & Wynne, 1984). For IAM participants, these arguments shifted the bounds of conversation into such an unfamiliar shape that all their initial responses showed a misunderstanding of such critique, which they viewed as accusations that the IAM community supports BECCS deployment, and that models do predictive work. They then fell back upon a characterization of the proper relationship between climate science and policy based on dispassionate investigation, institutional independence, and a purely advisory role. No modeler gave formal naming to this self-identification, but it reflects the tenets of Merton's (1973) resilient characterization of scientific expertise as 'on tap' in supplement to politics 'on top', and by extension, a separation between scientific authority and those of laypersons. By invoking the 'not policy prescriptive' IPCC mandate in characterizing the rationale and effects of IAM results, and by linking the feasibility of those results to the experimental nature of model structure, modelers emphasize that how decision-makers use science matters more than how science structures the bounds of possibility.

5.5.1 What implications might boundary work have for future IAM activity?

To be clear: it is not our intent to imply condemnation of IAM epistemology and practice. Rather, boundary work helps us to clarify the IAM community's sense of misplaced culpability. At the same time, we must recognize that boundary work has real consequences for the future shape and direction of the IAM enterprise, and we can see this particularly in proposals for reform. Participants arrived at corrective measures that were comparable at a high level, but the details conformed to preceding arguments that privileged particular perspectives.

Firstly, modelers saw improving feasibility as 'nudging' existing IAM processes, by adding real-world perspectives to modeling parameters (e.g. costs, technology diffusion rates). Critics, however, saw improving feasibility as part of a wider 'judging' of the IAM community's supposed capacity to legitimize unproven sociotechnical systems. In a second example, IAM participants rationalized the need for a greater spread of scenarios as a way to increase the 'solutions space' and confidence via further model application and inter-comparison. Some critics, by contrast, saw it as an opportunity to ask who is in the room to do the mapping, and increase confidence via inclusion, reflection, and objectives alternative to those posed by the RCPs.

Finally, emphases emerged on the shape of process transparency—this time, driven by differing conceptions of the role of scientists in politically charged research. IAM participants framed engagement as a clearer cautioning to policy makers in IPCC-UNFCCC interfaces that IAMs map rather than shape options, and as documentation of scenarios (and to a more limited degree, the structure of different models) via various databases. The first framing reinforces the boundary between IAMs as information providers and end-users as decision-makers; the second reflects a traditional mode of science communication where results rather than process are the objects of attention. Some critics, driven by perceptions of the technocratic and performative nature of IAM work, called for more fundamental re-designs—not just the scenarios themselves, but objectives, (non-expert) participants, model structure, and the relationship between IAM work and climate policy.

The former conception of critique and reform, then, is about expanding the research agenda: Delivering experimental but actionable evidence about various socio-technical approaches for tackling climate change by fine-tuning and increasing model application. This is borne out by the contextual literature: Critical assessments of BECCS and modeling work led by (integrated assessment) modelers tend to be review articles combined with prospective research agendas for widening the dimensions of BECCS' feasibility, where the limitations and variabilities of model structure are either hinted at but not interrogated (e.g. Tavoni & Socolow, 2013; Fuss et al., 2014; Smith et al., 2016; Minx et al., 2018; Fuss et al., 2018) or where reform is contested by perspectives internal to modeling practice (e.g. Gambhir et al., 2019). One partial exception calls for public debate on the policy options generated within assessments to feed back into refining the front-end of modeling (Edenhofer & Kowarsch, 2015). Yet, the object of critique here would be proposed strategies like BECCS, or emerging implications such as food security—not the IPCC Working Group III's structure of solution-oriented assessment.

The latter conception of reform, rather, is about interrogating the research mode: Questioning the motivations and structures of evidence-production upon which this research agenda is built. This difference is noteworthy. Within the former mode, activities thought by its proponents to be critical and self-reflective can proliferate, and will not endanger the system of knowledge production and the perceived relationship between science and policy represented by IAM activity in IPCC assessments. This reflects conclusions drawn by Shackley and Wynne (1996) regarding the interrogation of modeling on the physical science of climate change: operators of those models understood critique and reform within their existing practices, reinforcing rather than eroding the centrality of their work to climate assessment.

In turn, the mode of research has implications for how mitigation strategies will be mapped and framed. Ideas for more comprehensive reforms of IAM and WGIII activities are heterogeneous and remain at a high level of abstraction. But what might some effects be if the 'incumbent' modeling perspective remains inertial? The narratives and discursive structures of IAM work would make for rich study (Beck, 2018; Ellenbeck & Lilliestam, 2019), and it is already clear that research and discourse—e.g. exploring barriers to rollout, ambitious climate targets, 'overshoot' of global carbon budgets, normalization of carbon removal proposals, language framed around 'Net Negative' or 'Net Zero' emissions—is being shoehorned into futures shaped or reinforced by the presence of BECCS in scenarios that were meant only to be 'explorative' (see Beck & Mahony, 2018; Geden et al., 2019). But it is not simply the products of modeling—BECCS, the promise of negative emissions, or the IPCC pathways that incorporate them—that might be performative, but the system of production as well.

One concern centers on the expansion of the space that IAMs could possibly map, alongside a shift from the original objectives and coherence of the IAM community's restructuring of its work prior to the AR5 (see footnote i). The expansion of the 'scenarios space', seen as necessary to map the 'solutions space', may lead to a spread of new climate and sustainability targets, new technological and societal strategies, new framing assumptions and parameters, new expert communities to engage, new models to deploy. One can accept that a shifting scenario space is part of the evolving nature of climate assessment, but we must also be wary that this is not accompanied by an increasingly tenuous grasp of the overall content and direction of the literature. The Shared Socioeconomic Pathways (SSPs), representing variations on sociopolitical conditions, has since the release of AR5 resulted in hundreds of new studies (ICONICS n.d.), and overarching analyses have yet to be conducted—although this would likely have to be produced in the course of preparing the IPCC's Sixth Assessment Report. There have also been explorations of the value of reorienting the RCP-SSP framework for biodiversity assessments (e.g. Kok et al., 2017). What would happen if IAMs were purposed to map strategies to achieve the UN's benchmark Sustainable Development Goals?

Another concern follows the example set out by BECCS: that speculative technologies deployed in IAMs as back-stops for reaching ambitious targets become normalized due to a lack of credible alternative visions. Recall that this has been argued to follow a template once occupied by nuclear energy (Keepin & Wynne, 1984); our discussion need not be restricted to novel carbon sinks, but to innovations in energy systems, behavioral systems, carbon budgets, and other components that can be programmed into modeling as well. Is the next move to expand into IAMs other land-based approaches for negative emissions (Smith et al., 2016)? What would happen if the capacities of terrestrial carbon removal are exhausted in modeling work—does modeling then incorporate negative emissions approaches based in the marine environment, or technologically-grounded 'direct air capture' approaches, or methods for reflecting sunlight ('solar radiation management', SRM), on a similarly 'explorative' basis?

5.6 Conclusion

We echo calls to develop 'reflexive' or 'participatory' approaches to modeling as a pragmatic step to bridging perspectives. McLaren (2018) notes: 'Modeling should experiment with … designing trans-disciplinary research programs that genuinely engage with political, social and cultural dimensions of climate policy, not merely seeking to abstractly model the political and social alongside the scientific' (p. 218). Salter et al. (2010), through 'participatory integrated assessment', go further, highlighting modeling not only as a technocratic area of knowledge production in need of upstream stakeholder engagement, but as a tool capable of bridging the expertise of modelers and the concerns that drive users. Nose-to-tail engagement with a particular modeling process—as tool, political objective, project design, and dissemination—can teach modelers and decision-makers something about each other, and decisions will be more robust for it. In the short term, this dovetails with modeling proposals to introduce stakeholder feedback into the evaluation of modeling content, and connect these to designing a diversity of objectives and scenarios (Edenhofer & Kowarsch, 2015).

In the long run, reform would require re-evaluation of model structure, as there is sufficient debate within and external to economic modeling on the suitability of the current structure of IAMs for their stated mapping purposes (Gambhir et al., 2019; Ellenbeck & Lilliestam, 2019; Anderson & Jewell, 2019). Reform would also implicate the major institutions that manage the boundary between climate science and climate policy—the IPCC, in particular, cannot remain untouched (Hulme, 2016; Beck & Mahony, 2018). For the near future, individual projects might serve as expositions of the possibilities that such modeling affords, offering opportunities for learning and experimentation with different formats and approaches. We must note, in this vein, recent initiatives generated by modelers themselves. For example, the SENSES (n.d.) and DIPOL (n.d.) projects—housed at the Potsdam Institute for Climate Impacts Research, host to much resonant IAM work—organize collaborations between scientists and end-users to explore the front-end of modeling, and to produce needs-relevant scenarios.

We might recall that participants from the IAM community, in our interviews, noted that critique appeared to them a kind of 'drive by' criticism; it is therefore laudable that efforts to proactively grapple with concrete alternatives are not only undertaken by modelers, but have come to adopt the language of critics. We must ensure that these do not embody fringe initiatives that neither reflect, nor will be able to shift, the inertia of the IAM enterprise. We can observe this evolving space through the lens of boundary work, and look for the lurking presence and effects of different animating understandings of what the purposes and processes of reform should be. If modelers and critics of various disciplines see increasingly common frames of reference like 'co-production', 'scenario diversity', or the coordinating role of the IPCC, much like 'feasibility', through the prisms of their own worldviews, then we must navigate misunderstandings that could emerge once we scratch the surface of the reforms posed, due to the presence of different political projects that are still unfolding.

The emergence of BECCS has thrown a spotlight on IAM work, and both hope and caution are due in observing recent developments on the embrace of greater inclusivity. Our study points out the need—accompanied, promisingly, by some desire and action—towards a shared ethos and process between creators, translators, and users of these depictions of possibilities for mitigating climate change. And in future collaborations, we must recall that despite their resonance, IAMs are but one corner of climate governance, and remain wary that we do not treat improving model structures and scenarios as a proxy for inquiring more creatively and comprehensively after the kind of climate and civilization that we wish to have.

Table 5.1: Study participants

Background	Position / Institute	Engagement with BECCS debate
IAMs	Professor, University	IAM technical literature
IAMs	Professor, University	IAM technical literature; societal challenges
IAMs	Senior research leader, Global environment research institute	IAM technical literature
IAMs	Senior researcher, Global environment research institute	IAM technical literature
Models (Economic)	Senior research leader, Global environment policy institute	Technical and societal challenges; future research agendas
Models (Economic)	Senior research leader, Global environment research institute	Technical and societal challenges; critique of climate assessment structure
Models (Land-use)	Professor, University	Technical and societal challenges
Models (Vegetation)	Scientist, Global environment research institute	Environmental challenges
Science & Technology Studies	Senior researcher, Sustainability research institute	Critique of climate assessment structure
Science & Technology Studies	Lecturer, University	Critique of climate assessment structure
Policy	Researcher, Sustainability research institute	Societal challenges; governance structures
Policy	Senior research leader, Global policy institute	Technical and societal challenges; critique of climate assessment structure
Policy	Director, Global environment research institute	High level analysis of global climate policy

Table 5.2. 'Incumbent' perspective

Name	Ascribed to participants from:			
	IAMs (out of 4)	Models (4)	STS (2)	Policy (3)
A: Feasibility is not a direct representation of reality.	2	3		1
Model constraints form experimental conditions to test alternatives.	4	2		1
BECCS is unfairly singled out.	3	2		
Model and scenario diversity contextualize outliers.	2			1
IAMs navigate the tension between simplicity and complexity, and produce emergent insights.	4	2		
B: Research is 'explorative' - policy has to be taken as given.	4	3		1
Potential misuse should not deter explorative research.	4	2		
C: 'Map-making' widens the solutions space.	4	3		1

↳ Policymakers and researchers are capable of mutual understanding and collaboration.	3	1	1	
D: Quality control navigates need for verification and potential for misuse.	4	2		
↳ Modelers are working to close information gaps.	4	2		
E: Critics misunderstand ‘explorative’ work; constructive criticism needed on BECCS barriers.	4	2		
F: Try to improve feasibility in modeling inputs, and there are benefits to technical definition.	4	2		
↳ Greater scenario diversity underpinned by modeling logics.	3	1		
↳ Policy makers have responsibilities in understanding modeling limits.	2	2		

Table 5.3. ‘Critical’ perspective

Name	**Ascribed to participants from:**			
	IAMs (out of 4)	**Models (4)**	**STS (2)**	**Policy (3)**
A: Feasibility requires fidelity to reality.		2	1	2
↳ Modeling constraints are malleable enough to achieve any conclusions.		1		2
↳ New technologies can over-perform (e.g. nuclear).	2	2		1
↳ Outliers can be used as ‘silver bullets’.	1	1		3
↳ Internal complexity makes results inexplicable.		2		1
↳ Inter-comparisons may not improve model practice.	1	1	1	1
B: Research has to be a choice.	1	1		2
↳ Claiming neutrality avoids criticism.		1		2
↳ Financial incentives constrain agency.	1	2	1	1
↳ Policy objectives constrain agency.			2	2
C: IAMs frame viability and desirability.	2	1	2	2
↳ Modeled BECCS has performative effects.	1	1	2	2
↳ Researchers do not grasp policy-making.		1		3
↳ BECCS fulfills cynical political and policy functions.			1	2
D: IAM community focuses communication on results, not research process.		2	1	1
E: Modelers misunderstand critique; IAM work has to recognize its driving effects.		1	1	1
F: Redefining feasibility has to reflect some new understanding of IAM influences.		1	2	1
↳ Greater scenario diversity underpinned by equity concerns; implicates structural change at IPCC.		1	2	
↳ Modelers have primary responsibilities in engagement; co-design of modeling needed.		1	2	

Chapter 6

Engineering Imaginaries: Anticipatory foresight for solar radiation management governance

Since solar radiation management (SRM) technologies do not yet exist and capacities to model their impacts are limited, proposals for its governance are implicitly designed not around realities, but possibilities – baskets of risk and benefit that are often components of future imaginaries. This paper reports on the project Solar Radiation Management: Foresight for Governance (SRM4G), which aimed to encourage an anticipatory mode of thinking about the future of an engineered climate. Leveraging the participation of 15 scholars and practitioners heavily engaged in early conversations on SRM governance, SRM4G applied scenario construction to generate a set of alternative futures leading to 2030, each exercising different influences on the need for – and challenges associated with – development of SRM technologies. The scenarios then provided the context for the design of systems of governance with the capacity and legitimacy to respond to those challenges, and for the evaluation of the advantages and drawbacks of different options against a wide range of imaginary but plausible futures. SRM4G sought to initiate a conversation within the SRM research community on the capacity of foresight approaches to highlight the centrality of conceptions of the future to discussions of SRM's threats and opportunities, and in doing so, examined and challenged the assumptions embedded in conceptualizing SRM's aims, development and governance, and discussed the capacity of governance options to adapt to a wide range of possibilities.

Published as: Low, S. (2017). Engineering Imaginaries: Anticipatory foresight for solar radiation management governance. *Science of the Total Environment*, 580: 90-104.

This paper relied on the exceptional efforts of Miranda Boettcher and Johannes Gabriel in designing, organizing and curating 3 workshops that generated the data, as well as a workshop report. The credits for the workshops and report are:

- Low: Conceptualization; data curation; formal analysis; writing-original draft; writing-review and editing.
- Boettcher: Data curation; formal analysis; writing-original draft; writing-review and editing.
- Gabriel: Workshop design and facilitation; data curation; formal analysis; writing-original draft; writing-review and editing.

6.1 Governing solar radiation management

The controversial idea of solar radiation management (SRM) – a set of hypothetical approaches that suggest that reflecting a small portion of incoming sunlight back into space can reduce climate warming and mitigate some of its impacts – has in recent years been the subject of growing debate as a form of geoengineering or climate engineering, defined as deliberate and large-scale interventions in the climate system aimed at counteracting the impacts of climate change (Shepherd et al., 2009; IPCC, 2014; Schäfer et al., 2015).

SRM, however, does not exist as full-fledged technologies and deployment strategies, but as an early set of hypothetical proposals, research activities and discourses based largely within academic networks in the global North. Hardware development remains immature and un-scaled; national governments have yet to take clear positions on deployment or even the need for exploratory research. If SRM emerges into a complex landscape of issues, actors, and agendas in global politics, it will pose challenges at every stage from innovation to implementation. Early concerns may seem more tangible with emerging discussions on experimentation outside the lab (see Doughty 2014 for examples of past small-scale field tests; see Keith et al. 2014 for an initial typology of proposed future tests).

Questions of how to govern SRM have thus been central to early discussions. As with many emerging science and technology issues, a diverse research community of climate modellers, engineers, and ethical, legal and political scholars currently plays a constitutive role in conceptualizing the challenges implicated in the totality of 'engineering' the climate, as well as in proposing appropriate systems of governance – constellations of actors, practices and mechanisms seen as capable of navigating those challenges. However, these proposals operate under - or at least emphasize - different criteria and assumptions: the regulatory mandate and the technical or societal dimensions of its objectives, the range of climate engineering technologies addressed, the stage of innovation targeted (research, field-tests, deployment, or the full chain of development), the relevant actors to be engaged, the capacity and perceived legitimacy to make or enforce decisions, and reliance on legally-binding regulatory structures or on 'soft' policy options. Within this landscape, how can the merits or drawbacks of individual proposals be more symmetrically compared and evaluated?

6.2 Engineering imaginaries

This paper reports on Solar Radiation Management: Foresight for Governance (SRM4G), an anticipatory foresight (see section 4) project that sought to design and test a framework for adjudicating between the capacities of different SRM governance proposals by focusing on one particular set of assumptions embedded in them: the challenges that are emphasised as the most important for governance to navigate in the political landscape of the future (section 3). Since SRM technologies do not yet exist and capacities to model their impacts are limited, governance of activities from development to deployment is implicitly designed not around realities, but possibilities. Proposals refer to baskets of risk and benefit that are often components of visions of the future in which SRM research and deployment has (or has failed to) become a reality, positing a range of imaginary but compelling outcomes that influence how SRM is engaged with in the present.

A common concern in the near term is that even considering SRM research might cause states and other actors to reduce their mitigation and adaptation activities; a response might be to tie decision-making on SRM into the UNFCCC from its earliest stages (Honegger et al., 2013). The optics of outdoors experimentation may cause public outcry, or there may be perverse incentives from interest groups to promote, control, or disguise technology development. For these, some propose additional codes of conduct, responsible innovation frameworks, and disclosure mechanisms (Rayner et al., 2013; Stilgoe et al., 2013; Craik & Moore, 2013), (networks of) national research programs with oversight capacities (Long et al. 2010), and intellectual property governance (Reynolds et al., 2016).

At the same time, many argue that the challenges of an engineered climate cannot be discussed in isolation from the risks of the planet warming under current emissions pathways – that is, not researching or deploying SRM poses its own salient set of risks. These tend to place a emphasis on reducing ignorance and forestalling premature rejection through immediate research and field-experiments, and argue against overly burdensome multilateral governance at early stages in favour of more informal coordination between research networks and bottom-up norm creation to allow outdoors experiments to go ahead (Victor, 2008; Parson & Keith, 2013; Morgan et al., 2013; Parker, 2014). Still others perceive a clique of scientists heralding a technofix that might perpetuate the carbon economy and an exploitative relationship between more developed economies and the global South, or between human civilization and the natural world. One responding governance proposal is a moratorium on all outdoors experimentation (ETC, 2010).

In the longer term, there may be state-based competition over pursuit of technological capacity for deployment or over the proposed temperature of the 'global thermostat'. In the event of deployment, some fear that the uneven alteration of regional weather patterns would adversely affect lives and livelihoods, that establishing liability and compensation would be difficult, and that siloed national agendas, political brinksmanship, or outright conflict would result. Recognizing that these risks require governmental participation, responses range from minilateral clubs of technologically capable states or indispensible major emitters (Victor, 2008; Virgoe, 2008; Parson, 2014), or governance by one or several UN bodies (Honegger et al., 2013; Bodle & Oberthür, 2014; Lloyd & Oppenheimer 2014; Lin, 2015), depending on how one emphasizes the potential for different groupings of states or international bodies to mitigate or exacerbate those risks.

A comprehensive and evaluative review of all governance proposals is lacking in the literature, and is beyond the scope of this paper. The point that might suffice for our purposes is that many of the conceived challenges which motivate governance designs are future-oriented, have entwined technical, societal and environmental dimensions, and consist of cascading sequences of events that cannot be concretely predicted (for an examination of the deep uncertainties in forecasting climate engineering futures, see Chris, 2016). In many articulations, SRM contains emergent linkages with climate change and energy, state and human security, health, biodiversity, resource scarcity, intellectual property, science and technology as an escalating enterprise, and historic dynamics between major global powers. Such implications have to be generated in a way that relies as much upon the imaginations of researchers as their knowledge. Yet, these conceptions are subject to implicit, ambiguous assumptions about the shape of future developments, and to the biases that accompany the expertise of their proponents.

6.3 The SRM4G project: Using scenarios to explore the governance of SRM

Highlighting the influence that conceptions of the future exercise upon SRM regulatory designs can act as a lens through which the research community can assess the merits of different goals and building blocks of governance. This was the premise of Solar Radiation Management: Foresight for Governance (SRM4G): a collaborative project between the Institute for Advanced Sustainability Studies (a hybrid research institute and think tank on pathways toward global sustainability) and Foresight Intelligence (a strategic planning consultancy), upon which this paper elaborates (see also the workshop report at Boettcher et al., 2016).

The aims of SRM4G were to:

1. Initiate a conversation among researchers involved in early discussions on SRM governance regarding the capacity of foresight and scenarios approaches to methodologically ground discussions of governance design regarding such future-oriented technologies.
2. Highlight the centrality of conceptions of the future to discussions of the risks and benefits of SRM, and to consider an expansive range of challenges that cannot be derived from technical assessments or climate models.
3. Examine and challenge the assumptions embedded in conceptualising SRM's aims, development, and governance.
4. Evaluate how well SRM governance options perform under alternative societal, political and environmental conditions, and to discuss the capacity of (or the need for) SRM governance options to be adaptable or resilient to a wide range of possibilities.
5. Generate future-oriented discussion on governance designs, without providing policy advice on specific SRM governance mechanisms.

A relatively small number of 15 participants were drawn from researchers and practitioners involved in early conversations on SRM governance, with backgrounds in international law, (climate) politics and policy, ethics, and public engagement (see Table A.1, appendix). This was to reflect and target current nodes of research in Europe and North America, to create a multidisciplinary group combining a wide range of expertise and points of view, to ensure a high level of familiarity with the subject matter, and to allow for in-depth discussion and reflection.

Over the course of three workshops in 2015, SRM4G generated a set of alternative futures suitable for exploring environments and contingencies that SRM governance options might potentially navigate. The storylines and actor landscapes of these scenarios each exercised different influences on the need for – and challenges associated with – the development of SRM technologies. The scenarios then provided the context for designing governance systems with the capacity to respond to those challenges, and for evaluating the advantages and drawbacks of different options against a wide range of imaginary but plausible futures. It must be stressed that the scenarios developed were thought experiments, produced within the bounds of one method of scenario construction by a relatively homogeneous group of participants in a one-off exercise. With these limitations, there was no intent or capacity to predict the future of SRM development, or to pinpoint objective, necessary traits for governance strategies to adopt. Rather, the project explored how designing governance systems to address challenges that have not yet emerged might benefit from an anticipatory engagement with the future.

Section 6.4 will review the literature that underpinned the project's design, and section 6.5 introduces SRM4G's methodology in further detail. Section 6.6 reproduces the scenarios, while section 6.7 outlines the consequences of those scenarios for the governance of SRM and the design and evaluation of governance options. Sections 6.8 and 6.9 reflect upon the process, results, and implications for SRM governance.

6.4 Anticipatory foresight

A growing body of work in science and technology studies (STS) recognizes depictions of the future as essential to the shaping of discourse in emerging technologies: prospectively game-changing innovations whose most comprehensive impacts lie in the far future, yet are belied in the near term by immature and evolving technical foundations and political contexts (Rotolo et al., 2015). A main tenet of this literature is that emerging technologies often rely upon appeals to the future to generate support for their development, despite (or because) of the uncertainties and unknowns surrounding their future impacts. Such futures are constructed and contested, and are attached to implicit or instrumental claims about the proposed shape of present scientific and policy agendas. As a result, futures can examined as artifacts (things, words and deeds), and within the processes by which they are generated and shape how technologies are conceptualized, developed and regulated (see Selin, 2008 as well as the sociology of expectations, e.g. Borup et al., 2006). Future depictions are analyzed as expectations (van Lente, 2000; Brown & Michael, 2004; Borup et al., 2006), visions (Grunwald, 2004, 2013) and imaginaries (Fujimura, 2003; Jasanoff & Kim, 2015). Each term carries varying nuances on the actors, agendas, locales and dynamics by and within which they are generated, the timescale of the future over which they exercise claims, the probability or plausibility of their occurrence, and the intent for which they are created.

Recognizing these dynamics raises a second question. How can the fact that the future is more easily claimed than predicted be made explicit, and used in the service of governing emerging technology development in a manner that highlights the assumptions and agendas that influence innovation, that connects them to decision-making, and that extends the conversation to stakeholder groups beyond scientists and technologists? This is the essence of the anticipatory use of the future, marrying insights from decades of foresight practice in business, militaries and governments to the outputs of the STS literature (Selin, 2008). Futures can be designed - through scenarios, stakeholder dialogues, or even fiction - as an experimental space through which thought on possible (not predictable or inevitable) futures and options for response can be provoked, a communication platform for which to structure and integrate different future claims, and a petri dish within which the intellectual economy of participating stakeholders – as well as the staying power of the imaginaries themselves - can be subjected to further examination, and if need be, reflexive intervention (Grunwald, 2004; Selin, 2008; Barben et al., 2009). This brand of anticipatory foresight has adapted by STS scholars as a core component of several related frameworks for the governance of emerging technologies. Examples can be found in the use of scenarios for anticipatory governance (Selin, 2008; Guston, 2014), technology assessment (TA) for techno-visionary sciences (Coenen & Simakova 2013; Grunwald, 2013); vision assessment in future oriented technology assessment (Grunwald, 2004); and responsible research and innovation (Stilgoe et al., 2013).

SRM4G can also be situated within a third, smaller literature on the application of foresight techniques in climate engineering. Published works consist wholly of workshop reports, and range from a 'red-teaming' exercise that simulated strategic actions in constructing international governance mechanisms for climate engineering (Milkoreit et al., 2011), to explorative scenarios designed to trace the complex interactions of a broad range of factors and actors in imagined engineered climates of the future (over the next 50-100 years in Banerjee et al. 2013; over the next 15 years in Boettcher et al., 2015), to the extension of such scenarios to present implications for potential governance responses for a variety of climate engineering approaches (Bellamy & Healey, 2014) or SRM in particular (Haraguchi et al., 2015). The objectives and methods of SRM4G make use of explorative scenarios to assess governance for the development of SRM technology over the near term; Boettcher et al. 2015 do not explore governance mechanisms, and Bellamy and Healey 2014 deploy a less rigorous methodology for scenario construction while attempting a wide-ranging focus on governance for several different climate engineering approaches. SRM4G's methodology most closely mirrors that of Haraguchi et al. 2015, though with twice the scenarios, a more in-depth process for designing and evaluating governance systems, and the primary intent of specifically targeting 'insiders' in the research community on SRM governance to demonstrate the value of anticipatory thinking. To this end, SRM4G also situates itself in the literature on anticipation, with the intent of providing a theoretical anchor for past and future works on foresight in climate engineering.

6.5 Scenario construction methodology

6.5.1 Bounding conditions

SRM4G utilized explorative scenarios – inventing differentiated depictions of the future by alternating the outcomes of a broad array of environmental and societal developments, in order to force reflection on assumptions held by participants about those developments. These should be seen as distinct from policy scenarios, which plot alternative courses of action and their consequences for purposes of strategic planning. To anchor the details and plausibility of the scenarios, project designers set the timeframe over which generated futures would unfold over 15 years, from 2015 - 2030: a compromise between a wariness of generating scenarios involving a more imminent - but less plausible - development of SRM technologies (a timeframe of 5 years or less) and a longer timeframe (for instance, till 2050) in which the possible inclusion of barely recognizable developments would negate policy relevance.

Project designers chose to limit the scope of development in SRM to field experimentation of various objectives and scales of impact (Keith et al., 2014), with the upper boundary of such experimentation (in physical impact) set at a 'climate response test': a proposed category of field experiment aimed at understanding the response of the climate to radiative forcing perturbations at large scales and over a period of years (ibid). The designers originally intended for sustained, large-scale deployment of SRM technologies to be excluded from the scenario timeframes; participants would point out that at certain geophysical and temporal scales, experimentation and deployment might differ only in intent - a conceptual difference between preparing and actually doing. Nevertheless, while recognizing the indeterminate nature of this boundary, participants were asked to focus more on the challenges of governing technological development (from the small-scale on up) than the long-term maintenance of a fully-fledged planetary sunshade.

Whenever necessary, SRM was to be specified as stratospheric albedo modification (SAM) – the deployment of a layer of reflective particles in the upper atmosphere via technological means – due to its high profile in climate engineering assessments and the amount of attention paid both to its potential risks and its purportedly low direct implementation costs (McClellan et al., 2011). It should be recognized that SAM is only one approach to SRM, and the project risked a conflation of one particular technology with a much broader suite of sunlight-reflecting proposals toward which greater attention may be devoted as discourses and assessments further evolve (Bellamy et al., 2013).

Finally, it was assumed that SRM development could not be analysed without the contextualizing influence of developments in global climate governance. Participants, in considering the scope of the scenarios, would be asked to incorporate climate response strategies and innovations in carbon dioxide removal, mitigation, and adaptation measures alongside SRM development into account – defined in abbreviation as 'global responses to climate change in 2030'. It was therefore not a given for SRM development to be included in a given scenario, should some combination of background factors render it undesirable or obsolete as an option for addressing climate risks.

6.5.2 Exploring the broader context

After being presented with the bounding conditions, participants engaged in an 'environment scanning' process, identifying an expansive range of political, economic, social, technological, environmental, and other factors that they believed could shape global responses to climate change up till 2030 (see Table A.2, appendix).

6.5.3 Narrowing down to key uncertainties

Participants reduced the initial compilation of 48 factors to eight 'key uncertainties' (see Table 6.1, column 'Key Uncertainty Name') by conducting an 'uncertainty-impact analysis', using Morpheus, an online real-time assessment tool designed by Foresight Intelligence. The eight key uncertainties were - in the participants' collective estimation – the ones that might manifest in the highest variety of different outcomes in 2030 ('uncertainty'), and whose future manifestations might most strongly influence global responses to climate change ('impact').

Table 6.1. Key Uncertainties

Key Uncertainty Name	Short Definition	Current State (2015)	Projection A - Title	Projection A - Description	Projection B - Title	Projection B - Description	Projection C - Title	Projection C - Description	Projection D - Title	Projection D - Description
Perception of Climate Events/ Perception of Climate Change (Perceptions)	Seriousness, awareness and framings of climate change, causes and impacts by global publics.	Fragmented but widespread awareness. Concern variable, but often higher in more vulnerable regions. Framings highly contested.	Chronic concern	Chronic intensification of slow onset impacts drives global convergence of growing public concern. Fragmentation and contestation reduced.	Polarization by extremes	Extreme events and variability attributed to climate change raise salience and concern, but regionally variable with regard to vulnerability and capacity, generating polarized views on responses.	Shifting baselines	Chronic impacts grow slowly; competing concerns enable adaptive preferences to dominate. Concern stable or declining. Residual demands for climate responses still fragmented.	Variable + growing concern	Scale and extent of extreme events grows, with global repercussions, leading to widespread increase concern.
Domestic and Regional Stability (Stability)	Social, economic and political stability at domestic and regional scales.	Relatively stable. No regions in particular turmoil, but some flashpoints (e.g. Ukraine) and drivers of instability and concerns in many.	Major power destabilized	Substantial regional instability in a region of global political and economic significance: e.g. China turns inwards to address unrest resulting from inequality, pollution etc.	Peripheral regional instability	Multiple countries in a more peripheral global region experience instability (e.g. an 'African Spring'), with limited near term impacts on global climate response.	Stabilization	Instability declines or at worst remains dispersed, low-level, but chronic.	Multi-region instability	Social and political instability intensifies in many countries across multiple regions (responding to economic or climate stressors, or perhaps ideological values shifts and contagion).
CDR Technology Advancement (CDR)	Technologies to remove GHGs from the atmosphere and sequester them.	Techs are either at the concept stage or are economically infeasible.	'Saying No' Zero progress	Technologies proven to be economically unviable or have unacceptable social and environmental side effects. RCP2.6 discounted. Realization of the scale of locked-in climate change. Renewed pursuit of mitigation, along with increased support for SRM development.	'Honey Trap' Jam tomorrow	Always a tech of the future, but influences climate thinking especially with regard to mitigation. Large moral hazard effect, CDR has no effect on emissions. CDR becomes a resource sink for climate research funds (might be deployed in the future).	'Icarus' Rollout then backlash	Biological methods open for carbon credits. Dash for land. Suffering and backlash. CDR discredited. Step change for new GM CDR tech held back by public opposition.	'Pangloss' Cheap, robust, safe tech developed	Carbon price crystallizes based on CDR at $50/t. Each ton of emission matched by ton of removal. Rollout of tech underway by 2030. Countries and companies hold C liabilities on balance sheet. Carbon cleanup costs are less than 0.5 % of GDP.
Mitigation Technology Advancements/ Emissions 2030 (Emissions)	The extent, speed of adoption, and expected future pathways for GHG emissions at 2030.	Some tech in development, some emissions reduction commitments, some national and local actions, none of which have been enough to prevent GHG emissions from continuing to rise quickly.	'Indulgences' Fast emissions growth – BAU	Political smugness on some minor progress in changing the emissions growth trajectory. UNFCCC process grinds on, emitting more carbon than it saves. A global C cap-and-trade scheme is agreed, but it lacks bite and the C price drops to insignificant level. Sleepwalking towards disaster.	'Paradigm Shift'	Substantial transformation, whether in technology or political agreement. Emissions decline due to radical change. Breakthroughs in energy storage tech and ultra-low cost, ultra-high efficiency solar or major political breakthrough. Techs starting to come to market by 2030.	'Panic' Super fast emissions growth	India and Africa experience high growth rate and emissions trajectories. Panic over climate changes and projections. Continued finger pointing.	'Backlash' Hyper mitigation	Very aggressive mitigation on the back of a globally agreed carbon price. Markets adjust high costs to economies in the short term. Temps continue to rise. Backlash.
US-China relationship (G2)	The political and economic relationship between the US and China, as this relates to climate change and responses thereto. This includes how they relate to other global powers.	Economic and political non-adversarial rivals. They are major trading partners. They recently jointly announced their nonbinding commitments on the road to COP21. Background negotiations on climate responses continue, which in turn shapes others' response.	The happy couple	Increased trade. Military cooperation. Joint response to international crises including extreme weather events, climate migration, etc. Cooperation in scientific research, technology transfer, and climate responses.	Suspicious 'frenemies'	Continued status quo. 'Messy competition.' Second tier rivalry over territory and resources. Limited cooperation in scientific research, technology transfer, and climate responses.	The Dragon vs. the Eagle	Military threats. Proxy conflicts. Flare ups. Explicit territorial and resource conflict, potentially climate driven. Breakdown in cooperative behavior with respect to scientific research, technology transfer, and climate responses, impacting global cooperation on climate.	China crumbles	Social unrest leads to an end to Communist rule in China.
Acceptability of SRM (SRM)	How popular is SRM (field research) and is it perceived to be legitimate?	There is not widespread awareness of SRM.	Broad global support for SRM	SRM research (including field research) is widely supported, including 'elites', broader populations, global North and South.	International contestation	Support and opposition for SRM (field research) are held by significantly powerful blocks. This may (or may not) align along lines such as North-South or US-China-Europe etc.	Elite – popular split	Scientists and decision-makers worldwide are supportive of an SRM field research program. Resistance among broad populations/ environmental and social justice groups.	Broad global opposition for SRM	SRM research (including field research) is widely opposed, including 'elites', broader populations, global North and South.
Methane Feedbacks/ Severe Physicals Climate Impact (Climate Risk)	Severity of observed and expected climate impacts.	See IPCC Summary for Policy Makers in Fifth Assessment Report of 2013.	Climate Schmimate	Small temperature change than anticipated, ocean absorbs larger amount of energy, carbon cycle feedbacks moderate, moderate impacts of climate change realized, some suffering. Improved understanding leads to projections of climate change being less severe.	Hot mess	Temperatures rise rapidly, climate sensitivity estimates revised upwards, ocean absorbs less energy, arctic ice free in summer. Impacts of climate are evident in many regions, including the Global North. Uncertainty on key climate factors reduced (e.g. climate sensitivity, etc.).	Biome bomb	Temperature rise continues, no great improvements in projections. Impacts of climate change become more severe, especially in sub tropical regions. Severe climate/earth-system shift, e.g. Amazon die-back, large-scale permafrost collapse, weak monsoon.	Disparate climate	Moderate temperature increase, carbon, etc. Regional projections very wrong, regional differences larger than expected, e.g. larger warming in arctic, less in tropics AND larger regional hydrological differences. i.e. change in winners and losers of climate change.
Global Economic Stability (Economic Stability)	General trends and events affecting global economy, incl. recessions, growth, distribution.	(Dubious) economic recovery after recession. Some risks to stability reduced, others not. Significant inequality, growing in many regions.	Developing nations surge	Global growth continues but is dominated by 'developing' nations; 'Western' nations show little growth. Global inequality reduced but domestic inequality rises.	That's not fair	Global economic growth with strong technological advancements: increasing inequality of income and wealth is concentrated in fewer hands (global phenomena).	Swamp economy	Global growth stalls, by 2030 more-or-less no growth. Massive recession in US, some developing nations catch up with developed nations.	The greatest recession	2029 massive economic crash, international finance system frozen.

6.5.4 Creating projections for key uncertainties

Participants developed four distinct, alternative 'projections' of each key uncertainty in 2030 (see Table 6.1, columns on Projections A, B, C and D). The goal was to emphasize the potentially wide range of outcomes of each uncertainty within a 15-year time period by breaking them up from umbrella concepts into specific versions of the future; and to thereby create sets of projections that would serve as the basis for the scenario frameworks.

6.5.5 Analysing consistency and selecting scenario frameworks

Each scenario framework was to be formed by a package of one projection from each of the eight key uncertainties, acting as the skeleton upon which the fully developed scenarios would be built. Participants undertook a consistency analysis to narrow down the range of possible scenario frameworks (around 65,000 possibilities) to those that were most internally consistent- that is, none of the eight projections contained in a given framework could contradict the other projections. Participants evaluated the consistency of each projection against the conditions of the others (from 1 = mutually exclusive, 2 = conflicting, 3 = orthogonal, 4 = facilitative 5 = mutually reinforcing). A computer program (utilizing a so-called branch-and-bound algorithm) then filtered through approximately 100 consistent frameworks. Project designers pre-selected the 15 most distinct scenario frameworks, out of which participants chose four for further development based on variety, potential worst cases, and potential best cases (see Table 6.2).

Table 6.2 Participants chose four scenario frameworks for further development, based on a variety of uncertainty projections.

		Fragmented	Sandcastles	Creek	Lucky
Perceptions	1A Chronic concern			■	
	1B Polarization by extremes	■			
	1C Shifting baselines				■
	1D Variable + growing concern		■		
Stability	2A Major power destabilized				
	2B Peripheral regional instability		■		
	2C Stabilization			■	■
	2D Multi-region instability	■			
CDR	3A 'Saying No' Zero progress			■	
	3B 'Honey Trap' Jam tomorrow	*			■
	3C 'Icarus' Rollout then backlash	■			
	3D'Pangloss' Cheap, robust, safe tech developed		■		
Emissions	4A 'Indulgences' Fast emissions growth (BAU)	■			
	4B 'Paradigm shift'		■		■
	4C 'Panic' Super fast emissions growth	*		■	
	4D 'Backlash' Hyper mitigation				
G2	5A The happy couple			■	
	5B Suspicious 'frenemies'		■		■
	5C The dragon vs. the eagle				
	5D China crumbles	■			
SRM	6A Broad global support for SRM			■	
	6B International contestation	■			
	6C Elite-popular split		■		
	6D Broad global opposition for SRM				■
Climate risk	7A Climate Schmimate				■

	7B Hot mess			■	
	7C Biome bomb		■		
	7D Disparate climate	■			
Economic stability	8A Developing nations surge			■	■
	8B That's not fair	■	■		
	8C Swamp economy				
	8D The greatest recession				

*Originally computed results

6.5.6 Creating pictures and histories of the future

Dividing into four breakout groups, participants fleshed out the projections contained in the abstract scenario frameworks into full scenarios: coherent 'pictures' of the future in 2030, as well as a corresponding 'history' leading up to it. The illustration of a coherent chain of events over the 15-year timeframe served as a plausibility check on the scenarios. In addition, all scenarios were presented in plenary, and were refined to correct inconsistencies and implausibilities brought up by other participants. The scenarios that follow are shortened and streamlined due to space constraints; the original versions can be found in the workshop report (Boettcher et al., 2016).

6.6 Scenario descriptions

6.6.1 Fragmented world struggles to handle unpredictable climate ('Fragmented world')

In 2030, climate change is having more diverse and negative regional impacts than was expected in 2015. The hydrological cycle has been severely affected, especially in Europe and Africa, and effective adaptation is proving difficult due to the unpredictability of impacts and higher-than-expected costs. A series of post-Paris COPs had ended in deadlock, and a global economic downturn had resulted in less investment into renewable energy. In 2018, as support for the UNFCCC waned, high hopes were placed on CDR approaches- particularly bioenergy CCS. However, as farmers swapped growing crops for biomass, food prices rose. Hoping for insulation from a prospective food crisis, the EU, US and Africa engaged in an escalating series of trade barriers *[CDR: 'Icarus' Rollout then backlash]*, whose climate of protectionism would play a pivotal role in the abandonment of the UNFCCC process in 2021. Mitigation failures, disparate climatic impacts, and increasing regional instability would dovetail in a cascading sequence of events that would entrench widespread perceptions of 'winners and losers' *[Climate risk: Disparate climate; Perceptions: Polarization by extremes]*. From 2023 onward, China's attention would turn inward to reviving its economic growth and maintaining societal stability, making engagement with a global climate strategy a non-issue *[G2: China crumbles]*. Withdrawal of Chinese FDI would cause a further African downturn; African refugees would flock to the EU, whose unity and overarching organizational structure, coupled with its own economic and climatic troubles, would collapse under the weight. Meanwhile, relationships would deteriorate between these states and other powers that would view their own situations more optimistically. The US, as a result of previous trade wars, refused aid to the EU. The US, Russia and Canada would also come to see benefits in crop growth and resource exploitation as the Arctic began to thaw, and Brazil would become a global player with the discover of new shale gas reserves *[Emissions: 'Indulgences' Fast emissions growth-BAU; Stability: Multi-region instability; Economic* *stability: Developing country surge]*. By 2030, a complex of global security, climate response, and economic cooperation efforts have become deadlocked, contributing to uncoordinated and self-serving stances on the development of SRM. Germany, France, and the United Kingdom, with the support of several African countries and Australia, are pushing for the development of SRM techniques as a quick-fix, while Brazil is interested in SRM as a means to optimise its climate and accelerate economic development. Russia, Canada, and the US believe they are benefiting from climate change and strongly oppose SRM *[SRM: International contestation]*.

6.6.2 Building sandcastles under the shadow of a tidal wave ('Sandcastles')

By 2030, concerted mitigation efforts have been accepted as the international community's central climate response policy. From 2017-2022, a critical mass of global powers were affected by a series of extreme climatic events - a monsoon failure in India, droughts in China and the US, and a wavering of the jet stream in Europe had led to tremendous dislocation and pressure to collectively and definitively reengage with the climate issue *[Perceptions: Variable with growing concern]*. Emissions would be successfully decoupled from economic growth due to breakthroughs in energy storage and renewable energy technologies, and adaptation spending would remain high *[Emissions: Paradigm shift]*. As the US and China, united by the effects of drought, drove the institution of a global carbon price in 2023, CDR technologies became cost-effective and would be deployed on a large scale *[CDR: 'Pangloss' Cheap, robust, safe technology development]*. Despite the paradigm shift, revised IPCC estimates highlighted that climate sensitivity had been previously underestimated, and that unanticipated climatic feedback loops - the disruption of the monsoon cycle, Amazon dieback, and the melting of Arctic caps- were irrevocably triggered *[Climate risk: Biome bomb]*. Recognizing this, the US would begin researching and developing SRM technologies, but when the first large-scale test in 2025 coincided with a hurricane devastating Miami, a nation-wide backlash resulted in a ban on SRM development in the US. Despite this, the US would provide financial and scientific support to a clandestine SRM research and development program in China. These efforts would come to an end *[G2: Suspicious 'frenemies']* when WikiLeaks released details about the China-US program in 2028, which was then unfairly identified as the cause of the diversion and flooding of the Yellow River two years before- an uncommon but unrelated ecological event. By 2030, attribution of extreme climate events to SRM testing - accompanied by CDR industry advertising campaigns seeking to promote CDR as 'safe and natural' in comparison to the 'dangerous technofix' of SRM – has fuelled widespread public fears as well as environmental and human rights groups' vehement objections to further interference with the climate. At the same time, many government leaders continue to insist that CDR would not halt the massive climatic changes already been set in motion, and that they lack both the financial resources and the time to adequately adapt. Therefore, while global publics continue to insist on mitigation and CDR activities, many suspect that their governments are secretly continuing SRM testing *[SRM: Elite-popular split]*.

6.6.3 Up the proverbial creek without a paddle ('Creek')

By 2030, the impacts of climate change are causing global panic; the result of a failure of the UNFCCC process due to a prevailing paradigm of economic development. In 2017, a number of 'drilling bonanzas' took place in increasingly accessible Arctic waters, and new coal gasification technologies made the exploitation of unconventional coal reserves possible. From 2018-2024, growing economic co-dependence led the US to support Chinese aspirations in the South China Sea in return for favourable trade deals; both powers would tactically ignore growing signs of climate risk highlighted by IPCC reports *[G2: Happy couple]*. Eventually, citing US-China hypocrisy and their own right to develop, India would turn to coal gasification instead of renewables, and Uganda would open the world's largest coal mine to fuel the 'East African Miracle'. Later, members of the South Asian Association for Regional Cooperation and the African Union would withdraw from the UNFCCC, causing its disbanding *[Economic stability: Developing nation surge; Emissions: 'Panic' Super fast emissions growth]*. Reckless growth was accompanied by failure to develop CDR. Beginning in 2017, a number of countries would look to CDR as a compensatory measure for burgeoning emissions growth. However, by 2019, bioenergy CCS was deemed unviable due to conflicts resulting from agricultural land-grabs by companies seeking government subsidies, and subsequent investments in direct air capture suffered setbacks due to leakages at storage sites. By 2026, unfavourable assessments had led to a collapse in CDR funding *[CDR: 'Saying no' zero progress]*. By 2030, ice-free Arctic summers, Amazon dieback, extreme weather events and food shortages are causing widespread suffering, and most of the world's population believes the climate system is on the brink of collapse *[Perceptions: Chronic concern for climate change; Climate risk: Hot mess]*. Desperate for a quick response, civil societies and governments are calling for the rapid deployment of SRM. However, as little research has been carried out in the last 15 years, the international community lacks the knowledge and tested capability to safely and effectively deploy SRM. An initial conference at Asilomar in 2018 had established a moratorium on large-scale tests in the absence of appropriate governance; as time passed and all hope was placed on CDR development, a state of limbo had become inertial. Now the international community is pooling their resources to revive SRM development: the Arctic Council are endorsing an international research call, Indian and Saudi prizes are announced for the first testable SRM technology, the US and China are setting up a joint research centre; and Boeing is announcing the development of deployment aircraft. Yet, it is becoming clear that public and political momentum is likely to lead to rushed deployment with little understanding of the consequences *[SRM: Broad global support for SRM]*.

6.6.4 Life's easy when you're lucky ('Lucky')

By 2030, climate change is no longer a serious concern. This had not always been the case; extreme heat waves and droughts in the United States, China, India, and Sub-Saharan Africa between 2016 and 2018 drove support for both SRM and CDR development. The situation changed dramatically due to the invention in 2020 of a revolutionary lithium-oxygen battery in a US government lab. The inventors, recognizing the commercial and strategic implications of their innovation for the global energy economy, conspired with sympathetic government officials to place it outside the realm of compulsory licensing. At COP 27 in 2021, they directed American climate negotiators to offer an expansive technology transfer system (which they characterised as a concession) in order to secure developing world consensus on an unambitious climate plan. The researchers then publicly revealed their invention. The technology transfer deal effectively removed intellectual property rights from the battery, and it was legally and freely distributed around the world, catalysing a green energy revolution in the mid-2020s *[Emissions: Paradigm shift]*. The economies of industrialised nations began to plateau as international finance, and technology development became more evenly distributed around the globe. This was especially noticeable with the creation of the 'Afrozone' in 2028, which solidified a large number of African states into a single currency-trading block *[Stability: Stabilization; Economic stability: Developing nations surge]*. As emissions growth slowed, the issue of climate change began to seem less serious. This perception was reinforced by the fact that climate patterns in the US, China and India re-stabilised in 2020, and although rainfall patterns in Africa continued to fluctuate, its infrastructure was better equipped to deal with these effects *[Climate risk: Climate schimate]*. Moreover, in 2024, the IPCC's estimates of climate sensitivity were revised, indicating that only moderate changes to the climate, with the exception of long-term effects of carbon uptake in the oceans *[Perceptions: Shifting baselines]*. Yet, public belief in long-promised breakthroughs in CDR technologies meant that the latter was not considered a politically salient risk *[CDR: Honey Trap]*. With low climate sensitivity indicating fewer near-term risks and with development of CDR expected to reduce the long-term risks from the greenhouse gases already released, SRM research is broadly opposed as a relic of the past by 2030. Only a few constituencies maintain support for SRM: scientists concerned that the promise of CDR may not materialise; 'neo-denialists' convinced of political motivations behind the IPCC's revised results on climate sensitivity, and 'deep greens' worried about preserving endangered ecosystems *[SRM: Broad global opposition for SRM]*.

6.7. Designing governance to respond to the scenarios

The intent behind developing these scenarios was to pose challenges that governance for SRM technology development would need to navigate. The following step was to elaborate upon what these might be. In the same breakout groups that created the scenarios, participants produced a list of potential opportunities for and threats to SRM governance presented by their respective scenarios in order to paint a comprehensive picture of the positive or negative conditions under which SRM governance would have to function in each hypothetical future.

Each breakout group then developed an SRM governance framework with the effectiveness, feasibility and legitimacy to mitigate threats and leverage opportunities presented by their scenarios. Participants were asked to make use of their high familiarity with the landscape of existing governance proposals and to incorporate relevant institutions, mechanisms and concepts as they saw fit, from bottom-up or self-governance mechanisms to highly institutionalised international organisations.

Four main components were incorporated to ensure comparability:

- Regulatory mandate
- Membership
- Structures, mechanisms, decision-making procedures
- Outputs and decisions

6.7.1 Opportunities and threats and responding governance designs

Below, two tables are presented for each scenario: one on the opportunities and threats, and a second detailing the corresponding governance options.

Table 6.3 Opportunities and threats: Fragmented world struggles to handle unpredictable climate

Opportunities	Threats
International contestation over SRM creates demand for governance	International contestation, in general and specifically over climate and SRM, likely to block agreement
Chance of influential norms emerging among states, similar to nuclear non-first strike use during Cold War	High potential for SRM implementation by a small number of states, contrary to the desires and interests of others
China's collapse reduces the number of major players on the international arena	China is a big uncertainty
Fragmentation could facilitate diversity of strategies and adaptability while avoiding lock-in	Potential for states to (want to) implement SRM in order to gain relative advantage over other states
Climate impacts (& high emissions and BECCS collapse) likely to put SRM governance on the agenda early	Unstable Europe is an uncertainty
India's intentions could broaden scope of SRM governance considerations to include SRM for purposes other than countering climate change	Quasi-emergency conditions could lead to hasty decisions and actions
Existing forum for international debate (UNFCCC) which may be resistant to discussing SRM is absent	Existing forum for international debate (UNFCCC, which is a logical site to discuss SRM) is absent
	Swamp economy may cause governments to focus on priorities that are higher than SRM

Table 6.4 SRM governance options: Fragmented world struggles to handle unpredictable climate

Name	Mandate	Membership	Structure and Mechanisms	Decisions/Outputs
Scientific advisory board	Provide sound advice concerning consequences	Scientific excellence with diversity criteria	Open public review Consensual but with publication of dissenting views	Periodic scientific summaries of evidence and argument Arms-length policy information
Non-scientific advisory bodies	Represent sectoral interests and perspectives	Security expertise; NGOs; environmentalists; ethics committee; union groups	Publicly minuted meetings, open reports	Reports and advice – unsolicited or by order
ICEO (International Climate Engineering Organization)	• Make positive contribution to climate policy as a whole • Ensure SRM potential is explored • Minimize risk of international conflict by: o Avoiding securitization of climate o Avoiding militarization of SRM o Avoiding sudden termination o Avoiding rogues • Comply with international norms • Minimize transboundary harm	Membership by qualification: • States • Non-state and Intergovernmental organizations linked in somehow Criteria for membership: • Good mitigators – e.g. falling carbon intensity/GDP • Contribute appropriately to global adaption efforts • Transparent, responsible research practice • Firewall between SRM and military	Parties form a General Assembly, which can: • Agree to CE implementation with a two-thirds majority of countries and global population (double majority). • Issue statements on a consensual basis (if need be, voting).	Double 2/3 majority lock for SRM deployment Compliance: • Facilitating compliance • Naming and shaming • Ejection • Good research practices • Dispute settlement forum • Talks towards mechanism for compensation fund • Research and intellectual property pool • Coordination of outdoor tests

Table 6.5 Opportunities and threats: Building sandcastles under the shadow of a tidal wave

Opportunities	Threats
Extreme effects of climate change lead to agreement on the 'need to act'	Emergency narrative could lead to normal rules being overwritten, leading to rushed decision-making on SRM
Emissions growth slowing could mean less SRM research is needed due to better mitigation	Environmental migration at record levels could lead to political pressure for 'quick fix'
Introduction of a significant revenue-neutral carbon price gives a clear signal for mitigation action	Development of low-cost energy storage could lead to less urgency for SRM governance/public discourse
Increased investment in adaptation to address climate change impacts leads to reduced mortality and avoided economic damage and less migration	CDR industry lobbying against SRM – commercial interests undermine legitimacy of the discourse. Lobbying power can distort the discourse on SRM governance
Low-cost solar/wind power leads to a low carbon economy	Hurricanes destroy Miami – Public backlash against SRM

which offers a way to safely exit SRM	research
Open research by the US off the coast of Florida could lead to a gain in scientific knowledge on SRM	Ban on SRM research in the USA – leads to research on SRM stalling and continued ignorance about the pros and cons of the technologies
Hurricanes destroy Miami – creates an opportunity for informed public discourse on the attribution of climate events	Decline of emissions leads to less impetus for SRM research, less information is entered into the SRM debate
Carbon price declines as CDR competition thrives, limiting one-sided lobbying power and windfall politics	Secret testing in China with US backing – secrecy undermines legitimacy of SRM discourse
Pathway to zero-carbon reduces pressure for SRM	Yellow River changes course, resulting in massive destruction – false attribution of extreme weather events to SRM testing leads to irrational decisions. Irrational public reaction leads to further elite-public polarization
Wiki-leaks reveals secret China/US SRM test – enhanced transparency	Backlash against SRM research leads to lack of information on which to make decisions
News of declining emissions empowers political momentum	
US-China agreement on carbon price strengthens mini-lateral decision making (could be positive for SRM governance)	US-China agreement on carbon price strengthens mini-lateral decision making (could be negative for SRM governance)

Table 6.6 SRM governance options: Building sandcastles under the shadow of a tidal wave

Name	Mandate	Membership	Structure and Mechanisms	Decisions/Outputs
Science-informed assessment of SRM	• Socio-technical assessments of implications at levels of deployment • Improve ability to attribute climate impacts	• Diverse: Scientists (diverse in disciplines social science, natural science researchers and policymakers • Representative internationally (i.e. science-policy body e.g., IPCC subgroup or independent)	• Mixed diverse panel defining guidelines (rather than treaty) • Working analogously to the London Convention (re the Law of the Sea) • Learning organization – iterative process with adaptive decision-making standards	• Determination of what constitutes a material termination effect and corresponding scale of deployment • Improved public discourse on attribution and impacts
Climate change emergency procedures	• Define 'climate change emergency' aka. Understand 'degrees of emergency' • Preventing irrevocable decisions; international norms	• Track 1: States emphasizing most vulnerable countries • Track 2: Civil society/ non-state actors/ earth systems	• Science-based: ○ Indicators on 'earth system vitals' ○ Monitoring of indicators ○ Scales of indicators defined • Values	• Minimum thresholds defined for consideration for declaration of an emergency • Procedures that can be put to work in a climate emergency including: ○ Do nothing ○ Disaster relief ○ Adaptation ○ Possible SRM ○ Deployment pathways incl. ○ Conditions & exit strategy ○ Outdoor tests
SRM Agreement	• Create procedures and deliberative processes • Establish conditions under which SRM could be deployed • Ensure adequate decision-making on SRM	• Countries (sufficiently representative) • Social science, natural science based information • Civil society	• Possibly a treaty • Possibly a moratorium linked to specific conditions under which it is lifted • Stage-gating initial • SRM deployment to ensure regular review and knowledge development to keep up with political decisions; • Preventing irrevocable decisions	• Physical monitoring systems to detect SRM deployment/ effects • Procedures in place that guide reactions to climate emergencies • Agreement on exit strategies & mitigation commitments as necessary conditions for SRM deployment/ allow for immediate exit without a material

				termination effect
Transparency	• Prevent mistrust and possible conflict by creating transparency in SRM research and potential SRM deployment	• Researchers and research organizations; (national or private) funding agencies • National governments (esp. with regard to militaries)	• Registry of research proposals and results of research open to the public • Content subject to public guidelines • The objective is to nudge researchers to disclose information in order to encourage their peers to do the same	• Publicly accessible data, information, and results on SRM • Enhanced academic/political debate; increased transparency • Increased Trust in research (and evidence-based decision-making processes) • Increased research coordination
SRM Ban	• Prevent SRM deployment • Ensure agreement is kept through sanctions and incentives • Monitor non-compliance	• UN Security Council/General Assembly/Minilateral group of countries • NGO observers	• Physical monitoring system to detect SRM deployment	• Ban • UN resolution

Table 6.7 Opportunities and threats: Up the proverbial creek without a paddle

Opportunities	Threats
US-China resolve South China Sea dispute – possibility of transcending 'territorial' or long-standing political/social conflicts, making cooperation easier (Belief: violence is bad, governance that encourages cooperation is good)	G2 dominance (global hegemony) privileges particular forms of governance (Belief: Diversity of governance is good)
Emerging economies converging with developed nations leads to better prospects for weaker/poorer societies to gain greater influence	Emerging economies converging with developed nations raises risk of more ingrained inequalities
India/China collaboration on SRM research – Independent/indigenous scientific capacity enhances autonomy and diversity (Belief: diversity and autonomy are good)	Global governance structure is basically reinforced (dissent reduced). (Belief: current economic order is incompatible with fair participative politics)
BECCS buried – stimulus for more integrated approach to governance of bio-productivity (for food, nature, forestry, Bio-CDR, energy etc. (Belief: integration is good for sustainability)	Declaration of climate emergency threatens diversity, participation, deliberation (Belief: deliberation and participation are good)
	SRM research patchy, scarce public funds - lack of international science governance means no coordination.(Belief: World would benefit from coordinated science)
	Oxford Principles on abstaining from SRM testing – self-regulation of SRM science could be undermined by Chinese culture or Indian rejection of 'colonial values' (Belief: Collaboration & integration are good)
	CDR land-grabs, conflict – descent into conflict and violence rather than peaceful and deliberative debate undermines governance (Belief: violence is bad)

Table 6.8 SRM governance options: Up the proverbial creek without a paddle

Name	Mandate	Membership	Structure and Mechanisms	Decisions/Outputs
Intergovernmental Office of Science (IGOS)	To evaluate, screen and govern science and technology of global relevance (including SRM)	National governments (ideally universal – 'inclusive' if 'mini-lateral'), represented by e.g. national academies or relevant government departments	Undertake assessments of technologies similar to ~IPCC; supported by public participation/deliberation; two stage process to assess first whether an area is 'in scope', and second, if so, to suggest how research should be governed and directed.	Assessments/ reports, if necessary protocols about the conduct of research and the nature of acceptable experiments (potentially extending to IP); funding
Safe Operating Space for Science (SOS-Science)	To promote responsible science on a voluntary basis	Self selected researchers, research institutions and NGOs	Voluntary, self-regulating network establishing and promoting a code of conduct for scientific	Code of conduct to preserve safe zone, serve as bar for funding outdoor tests

			research (including climate and climate engineering)	
Pope's Climate Governance Commission (PCGC)	Assess climate policy responses from cultural and ethical perspectives	Appointees – leaders from ethical, cultural and artistic communities	Issue and promote one or a series of reports	Broad evaluations of climate response options, suggesting new alternatives and encouraging ethical and sustainable cultural and behavioral change
Global Deliberative Exercise	To ensure full public participation and deliberation on questions of controversial technologies	Civil society/publics	Using – Worldwide views or similar organization/ methodology (online or f2f); nontraditional deliberative organizers	Inputs to other processes; legitimacy
Corporations/ Intellectual Property	To ensure that technologies are open access/public good	Aerospace, chemicals, etc.	Voluntary with broad stakeholder engagement (little profit potential)	Code of conduct, open access regime

Table 6.9 Opportunities and threats: Life's easy when you're lucky

Opportunities	Threats
	Promise of CDR reduces interest in SRM research
Effective mitigation can also be seen as an opportunity to limit SRM research	Effective mitigation is a threat to SRM research by limiting one side of the argument for it
Serious steps forward on mitigation would remove moral hazard effect and allow less fractious consideration of SRM making an institution easier to form	Following tech transfer revelation, US tightens up secrecy around government funded science on SRM
Energy revolution in the developing world – increased domestic capacity/self-determination regarding energy systems could increase climate/SRM conceptual category	Remaining climate risks seen as niche – Reduced perception of risk to humans risks creating environment that undervalues other species
New findings about the state of climate change take some of the heat out of climate discussion: Less acrimonious discussion of SRM	Creation of Afrozone – two distinct single currency zones create risk of excessive economic competition, negatively affecting scientific research
As developing economies boom, more balanced international arena allows for more equitable decision-making over SRM	Continued US-China competition reduces the likelihood of cooperation on SRM research governance
Strong scientific voices emphasizing climate insensitivity leads to reduction in interest in SRM when it looks like SRM is less necessary	Rejection of SRM could prove a threat if climate change is more severe than projected

Table 6.10. SRM governance options: Life's easy when you're lucky

Name	Mandate	Membership	Structure and Mechanisms	Decisions/Outputs
Inertial Dampeners	Smooth any excessive swings of opinion	• Existing science/ policy actors • Multiple modes of independent expert advice	• Low degree of institutionalization, as one would expect with a loose association of expert advisers • No attempts of individuals or groups to seek preeminent authority • P2P monitoring with expert community	Myriad outputs fed into policymaking at all levels
Transition Protocol	Transition out of climate SRM to planetary management SRM international norms	Concerned experts	Self-organizing group of concerned experts begin to lobby for consideration of the non-climate change uses of SRM	Members of loose expert networks begin to solicit for a formal institutional response to the prospect that SRM be used for non-climate goals

6.7.2 Cross-evaluating governance options

One of SRM4G's aims was to consider ways SRM governance mechanisms could be evaluated under conditions of deep uncertainty. Thus, participants were asked to seek 'robust' options that might prove capable, resilient or adaptable to navigating the widest variety of future conditions presented by the four scenarios, with the assumption that these might prove more capable under conditions of deep uncertainty than 'optimal' options that appear more adequate to deal with only one specific conception of the future (see Lempert et al., 2006, and Bellamy, 2015 for an application of the concept within the climate engineering literature).

This was conducted via a 'cross-evaluation' exercise. In breakout groups, participants were asked to stress-test and grade each of the four governance designs on their capacities to navigate the contingencies presented by the three scenarios apart from the particular scenario whose implications they were originally designed to address, via an ascending scale of 0-3. The scoring would provide a light initial assessment of the perceived robustness of the various governance structures and strategies, with the numerical grading intended as a prop for facilitating qualitative discussion rather than as objective values. Since any conclusions reached in this exercise would be necessarily limited by the simple methodology and small number of scenarios and participants, the cross-evaluation was intended to stimulate thinking among participants on the usefulness of robustness as a criterion for strategic governance design in the SRM context, rather than to deliver concrete recommendations for decision-making on governance.

As the cross-evaluation unfolded, participants encountered a number of difficulties in the exercise's design that compromised its value – these are detailed in the discussion section (6.8). The full results of the cross-evaluation were recorded, but will not be included here; rather, the following example, excerpted from the results, should illustrate the spirit of the exercise. One indication was that the governance options designed to govern SRM under the conditions of 'Fragmented world' might also be effective in all other scenarios. More specifically, an 'International Climate Engineering Organisation' including scientific and non-scientific advisory bodies (Table 4), could also help to avoid rushed decisions on SRM (as illustrated in 'Sandcastles'); it could help to avoid that the potential of SRM is not explored although needed (as illustrated in 'Creek'); and it could also help to avoid secrecy surrounding SRM research (as illustrated in 'Lucky').

6.8 Discussion

The sections below analyze the process and results of SRM4G, relying heavily on group discussions held amongst workshop participants. The ordering of the discussion sections follows the unfolding of the project, from the scenario construction methodology (6.8.1), to the scenarios and their implications (6.8.2), to the design of responding governance mechanisms and the cross-evaluation (6.8.3). The paper concludes with an examination of the fit between the project's aims and conclusions reached by participants (6.8.4).

6.8.1 Scenario construction methodology

Navel-gazing: Concern was expressed that the project's primary aim to enable future-oriented deliberations on SRM governance created a predisposition to developing uncertainties and (with one exception) scenarios that overemphasized the centrality of SRM to the unfolding of global politics. Although scenario exercises must tolerate a degree of emphasis relating to their chosen topic of investigation, methodological steps can be taken to encourage symmetrical assessment of different options for addressing climate change (see for example Bellamy et al. 2013). Within the context of this project, designers sought to ground SRM development and governance within a wider array of factors (sections 6.5.2-6.5.4) and global responses to address climate change that would include innovations in strategies for carbon dioxide removal, mitigation and adaptation (section 6.5.1). A result of this design condition was the development of one scenario ('Lucky') in which innovations in energy storage contributed to the perceived obsolescence of SRM (see also section 6.8.2).

Timeframe and extreme projections: The 15-year period (section 6.5.1) over which scenarios were designed to unfold left little room for significant change from the perspective of climate science, which operates on scales of decades to centuries, while simultaneously allowing room for more comprehensive shifts in (climate) politics and policy that operate on much shorter horizons. For example, some participants raised concerns that the projections of 'Climate Risk' (Table 6.2) were unlikely to plausibly occur by 2030. Indeed, despite repeated plausibility checks, the group generally identified a bias towards extreme change in the definition of the key uncertainties' projections, which could have been a result of efforts to avoid the status-quo bias that is common in scenario construction. Nevertheless, the group concluded that an additional review with a particular focus on climate science aspects was needed to temper these extremes without changing the scenarios' core narratives.

Group composition and biases: The project targeted a particular community of SRM governance researchers, which contributed to a participant make-up of predominantly male social scientists from western countries. It was suggested that the fairly homogeneous composition might have resulted in a narrower set of perspectives and more commonly-held guiding assumptions, and that future exercises might be broadened to include, for instance, more women, greater international and ethnic diversity, and other professional and disciplinary backgrounds such as economists and climate scientists. The underrepresentation of the lattermost discipline was seen as contributing to some of the more extreme climatic events that drove the scenario narratives.

Misleading empiricism: Certain steps of the scenario construction process (section 6.5) – particularly the uncertainty-impact analysis (5.3) and consistency analysis (6.5.5) – were excessively reliant on assigning numerical values to prioritize what uncertainties would form the basis of the scenarios, disguising the innately qualitative discussions. However, the figures also structured discussions by forcing participants to make the assumptions on which they made qualitative choices explicit.

Communication between 'insiders and outsiders': The full range of nuances communicated between participants cannot always be conveyed via finalized scenarios to those external to the deliberations. Participants were worried that readers might take reify or instrumentalize scenarios seen as plausible; alternatively, scenarios perceived as implausible might undermine the authors' credibility. It was agreed that the best way to communicate results without risking misinterpretation was to be as transparent and detailed as possible about the scenarios construction process and in reflecting upon them.

Embeddedness vs. neutrality: The STS literature has noted a tension in the role of scientists engaged in researching emerging technologies, between acting as neutral and academic analysts, and as practitioners implicated in shaping the technologies and perspectives of the field in which they are embedded; this is similarly true in the context of developing scenarios that envision future visions of technological usage (Selin 2008). This friction may have contributed to the fear of scenario reification or loss of credibility noted previously.

6.8.2 Scenario trends and their implications for governance

SRM challenges situated within wider political context: Participants highlighted that not only climate impacts and technological advancements affect future pathways; social, cultural, and political factors, their interactions, and an intersecting range of global governance issues were considered significant. For example, the confrontational conditions of 'Fragmented world' were not solely due to conflicts over SRM, but economic protectionism, migration, and security. Conversely, in 'Creek' closer US-China cooperation on climate response strategies emerged not primarily because of climatic impacts, but because of closer cooperation in trade and security affairs. 'Sandcastles' indicated that even if climate impacts seemed to indicate a case for SRM, social and cultural conditions could lead public or political opinion away from SRM.

Implications of different kinds of political division: In both 'Fragmented world' and 'Sandcastles', global politics was marked by strong stylized divisions; horizontally in the former (by regions), and vertically in the latter (by public-elite split), exercising different influences on how research of SRM was supported or opposed. The public-elite split in 'Sandcastles' regarding SRM was also triggered by misattribution of climate impacts. The combination of this misattribution and the secrecy surrounding SRM field tests highlighted the potential for broad public backlash against SRM after some initial support.

Ignorance and path-dependence: One difference between 'Sandcastles' and 'Creek' was the influence of previous efforts at mitigation on SRM development despite the presence of extreme climatic events in both. In the former, previous efforts at coordinated mitigation contributed to careful SRM development efforts, and in the latter, failure to forge prior global mitigation strategies contributed to more reckless SRM research. 'Creek' also illustrated potential risks of facing a climate crisis with a lack of SRM knowledge, partly because governance structures for SRM research had not been developed. This scenario suggests the relevance of early and ongoing discussions regarding governance structures for SRM research and development, including field-testing.

Conditions and implications of avoiding SRM: 'Lucky' was the only scenario in which SRM was neither considered nor researched with the intent of eventual deployment, perhaps providing an indication of the conditions that might de-incentivize SRM research (successful innovations in mitigation and low climate sensitivity), as well as an exercise in 'what governance does when there's nothing to govern.' It should be noted that this scenario was triggered by a significant event (renewable energy innovation) of low probability, but participants did not consider this a 'wild card'. A third discussion point raised was for an unintended consequence of successful mitigation: within the context of the scenario, mitigation and low climate sensitivity had the potential to lessen the effects of abrupt termination of SRM deployment, and therefore make deployment seem less risky.

6.8.3 Governance designs and cross-evaluation

Common core governance elements: From three of the four scenarios ('Fragmented world', 'Sandcastles' and 'Creek'), governance systems that contained similar core elements were derived: a scientific body to undertake interdisciplinary assessments of SRM development; a variety of bodies to incorporate the concerns of stakeholder groups; and an ideally multilateral state-based organization to establish conditions for deployment. There were elements more unique to particular scenarios; the high prevalence of environmental disasters in 'Sandcastles' led to an emphasis on procedures for determining what constitutes a 'climate emergency' to guide eventual SRM deployment, and in 'Creek', participants emphasized the need for more innovative forms of including the global public and intellectual property controls to temper a reckless and potentially technocratic rush to deployment. More so than the others, the multilateral organization designed in 'Fragmented world' emphasized conditions and procedures for decision-making and compliance, reflecting the extreme political disunity of the scenario. The exception was the informal, science network-based governance system from 'Lucky', which was designed to provide assessment of two opposing directions for (largely discredited) SRM: preventing sudden shifts in political opinion regarding SRM, and considering its use for other, non-climate change purposes, such as planetary management.

Informal governance has a (limited) window of usefulness: While transparency and scientific principles were considered essential minimal SRM governance mechanisms, they were not sufficient over time to govern SRM effectively under the conditions that evolved in the scenarios pathways, indicating that more formalized governance approaches might need to be considered; or that at the least, more informal governance mechanisms at the upstream stages of development need to evolve into institutionalized governance arrangements. The benefits of initiating SRM research governance sooner rather than later were highlighted, as it became clear that separating governance of SRM research and deployment was difficult under the circumstances described in some of the scenarios. This may indicate a perspective regarding a grey line in politicized agendas and contexts (if not in climatic impact) between technological development and deployment, and that governance may need to be seen as a pathway in which earlier efforts – and forms of governance - influence latter ones.

Exploring robust governance: The cross-evaluation (section 6.7.2) sought to explore which governance options were most capable of navigating the widest range of contingencies presented by the scenarios; and in answering the first question, to probe whether 'robustness' was a valuable criterion for designing governance. However, methodological and conceptual difficulties contributed to inconclusive discussions on both questions. As a time-saving measure, assessing the fit between each of the four governance systems and the scenarios was conducted not in plenary, which might have facilitated common understanding, but in individual breakout groups. This led to subjective understandings of the grading process, and unsystematic scoring of the robustness of the various governance designs. To avoid reification, participants and designers agreed that the results would not be published. Due to these difficulties, the cross-evaluation results provided an insufficient platform for participants to judge the value of robustness. While participants were broadly supportive of the concept, some also questioned if seeking robustness might perversely result in solutions of the lowest common denominator, or if navigating the widest possible spectrum of risks rather than specialized ones tends to 'flatten' the significance of particular challenges in relation to others.

6.9 Conclusion

In sum, how did SRM4G's conduct and conclusions match up against its aims (see section 6.3)? Feedback from participants suggested that scenarios can facilitate interdisciplinary communication and group learning, and that the project was successful in emphasizing the social construction of (managing) future risks in SRM (aim 1). The process proved especially useful in helping participants contextualise their thinking about SRM technologies; it allowed participants to think outside their respective disciplines to conceptualise complex future contexts, which helped to broaden their perspectives on challenges that SRM governance may face (aims 1 and 2). The scenario construction process also forced participants to make their assumptions about possible future developments explicit. In some cases the process helped them to rethink those assumptions and systematically explore new dynamics between climatic conditions, societal stakeholders, and governance systems (aim 3).

The project produced a useful initial evaluation of the merits of various structures and strategies for governance under alternative conditions (aim 4). Nevertheless, these conclusions should not be over-leveraged or seen as an exercise in prediction, and must be contextualized as a one-off set of cases generated by a small, relatively homogeneous group of participants that could only cover a limited spread of plausible futures. In addition, the creation of governance options and in particular the cross-evaluation exposed an emergent conflict between two project aims: to explore and evaluate the capacities of governance options against multiple futures (aim 4) without aiming for policy recommendations in favour of particular options (aim 5). Aim 4 required participants to assess how governance designs could make use of opportunities and avoid threats presented by the scenarios, both individually and collectively. However, such strategic planning is usually done within the context of policy agendas of particular governments or organisations, and SRM4G aimed to explicitly avoid providing policy advice on SRM governance mechanisms (aim 5). This lack of a concrete policy context created a paradox in which participants were left without a decision-making framework, since they saw their role not as planners for particular constituencies but as meta-analysts. Hence, in line with the project's aims, participants preferred to highlight the value of evaluating the scenario development process as a method of furthering deliberation on SRM governance.

A next step would therefore be to expand SRM4G's user community through spin-off exercises; this might contextualize and compensate for limitations in the original project's scope, participation and execution. The scenarios can and should be supplemented, supported or challenged by scenarios developed by different groups. The scenario construction methodology detailed here should allow follow-up projects to use the same boundary conditions and follow the same sequence of methodological steps, or to improve upon them. Smaller scenario projects could even use the intermediate results of this project to extend the set of scenarios developed using the key uncertainties and their respective projections. Furthermore, the scenarios described in this report could be used to test existing governance proposals, in order to make them more robust or comprehensive in the face of high uncertainty, or to gauge their value from the perspectives of particular constituencies. This could be done by individual researchers who have created governance proposals, or in a participatory group setting with an expanded range of stakeholders.

SRM4G should finally be situated within wider efforts to entrench anticipatory, future-oriented thinking in the discourse on SRM, climate engineering, and efforts to address climate change. Besides a limited but growing number scenario construction projects that explore future contexts and dynamics, or assess potential governance pathways, there have been suggestions for exercises to 'red-team' strategic actions in climate engineering development (Keith et al., 2010), or to envision futures towards – or against – which planning can be guided (Lin, 2015, p.47). The foresight toolbox has historically been the preserve of planning units in government, the military and the private sector. Yet, as part of responsible innovation or anticipatory governance frameworks, foresight can be deployed by research programs investigating the physical and societal dimensions of climate engineering to proactively explore research and policy gaps, and promote structured communication amongst the diverse constituencies implicated in shaping the ever-evolving landscape within which SRM and climate engineering- as an emerging discourse with many potential outcomes - must grow up.

Appendix

Table 6.A.1. Information on participants

Gender	Disciplinary background	Sector	Country where participant was professionally based
Male	Foresight methods and futures-thinking	Research / policy institute	United States
Male	Law	NGO	United States
Male	International relations; politics and sociology of climate change	University	United Kingdom
Male	Climate and energy policy	Research / policy institute	Germany
Male	International environmental law	Environmental NGO	United States
Male	Climate policy	Environmental consultancy	Switzerland
Male	Political science	University	United States
Male	Technological innovation and governance	University	United Kingdom
Male	Ethics; sustainable development, energy and climate issues	University; Freelance consultancy	Sweden
Female	Public perceptions and engagement	University	Germany
Female	Cognitive and imaginative process; futures-thinking	University	United States
Male	International relations; environment, food, and emerging technologies	University; Environmental NGO	United States
Male	Climate policy	Research / policy institute	Germany
Male	International relations; emerging technologies	Research / policy institute	Germany
Male	Global environmental politics	Environmental NGO	United States

Table 6.A.2. Initial compilation of factors that participants believed were significant for influencing global responses to address climate change till 2030

Factors	Notes
Food crisis	Regional vs. global implications; limitations on food trade; collapse of fishing
Scale of the fossil fuel sector	
Population growth and demography	E.g. Aging population
Methane feedbacks	E.g. Melting permafrost
Emissions in 2030	
Political leadership	
Climate research funding	
Ocean acidification	
Climate sensitivity	
Change in location and scale of formal power	E.g. between and within local / municipal level, national governments, international constellations
Strength and weakness of multilateral systems	E.g. IPCC, UNFCCC
Distribution of global power	Rise of emerging powers and their stances on climate change
Domestic and regional stability	E.g. break up of regional blocs or countries; socioeconomic instability
US-China relationship	
International climate conflicts	
New forms of international cooperation	E.g. minilateral 'clubs' emerge in place of multilateral system
Mitigation policy	E.g. carbon tax
Ideological change	New political paradigms
Artificial intelligence in governance	
Climate deniers advocate SAM globally	
Actors that benefit from climate change	E.g. Certain northern states; fossil fuel interests
Role of science in policy-making	
Deadlock in global mitigation efforts	
Establishing liability for fossil fuel emitters	
Corporate power	E.g. insurance and re-insurance industries; corporate capture of NGOs
Widespread enthusiasm for SAM	
Perception of climate events	E.g. catastrophism
Environmentally motivated violence	E.g. eco-fascism; eco-terrorism
Public perception of climate change	E.g. voters preference for CO_2 intensity; conspiracy theories
Retreat into the virtual world	Technological fetishism reduces engagement with sustainability issues
New participatory processes	E.g. global public internet-based participation in decision-making
Anti-modernism	Anti-science mentalities; political and religious extremism
Sufficiency movement	Reduced consumption and embrace of simplicity
Severe physical climate impacts	E.g. sea level rise; ice-free Arctic; biodiversity; loss of islands (states); species extinction
Extension of 'moral community'	E.g. to future generations or vulnerable communities
Diversity of decision-makers	
Role of NGOs	E.g. policy surveillance and implementation
Mitigation technology advancements	E.g. artificial intelligence; biological development; 3D printing; renewables; genetic engineering; energy storage
Adaptation capabilities	
Rising environmental migration	
Global inequality	E.g. growth in poorer countries
Global economic stability	E.g. capacity of a new recession to take attention away from climate change
Large volcanic eruption	
Scale of SRM field tests	From small-scale (examining atmospheric processes) to large scale (testing climate responses) tests; or none at all
Legitimacy of SRM field tests	Unilateral or multilateral implementation; covert or transparent
Structured assessment of SRM	Metrics for assessment; monitoring; attribution
CDR technology assessment	Scale; scope; price

Chapter 7

Conclusion

7.1 Thesis summary

The reader might find valuable a recollection of the thesis purpose, the research questions, and a summary of how these were addressed (see Table 1.1, reproduced below from Chapter 1). The purpose of this thesis was to explore recent proposals for novel carbon sinks (carbon removal) and sunshades (sunlight reflection) – often treated as forms of climate engineering, or deliberate and large-scale climate interventions – as case studies of emerging sociotechnical strategies in climate governance. I introduced the theatrical device of 'MacGuffins' as an anchor for how I regard future-based evidence on sunlight reflection and carbon removal – as resonant depictions of future implementation and associated challenges (what becomes known), but also as reflections of representation (who matters), procedure (how it is done), epistemology (how they know), and outcome (what happens and who benefits).

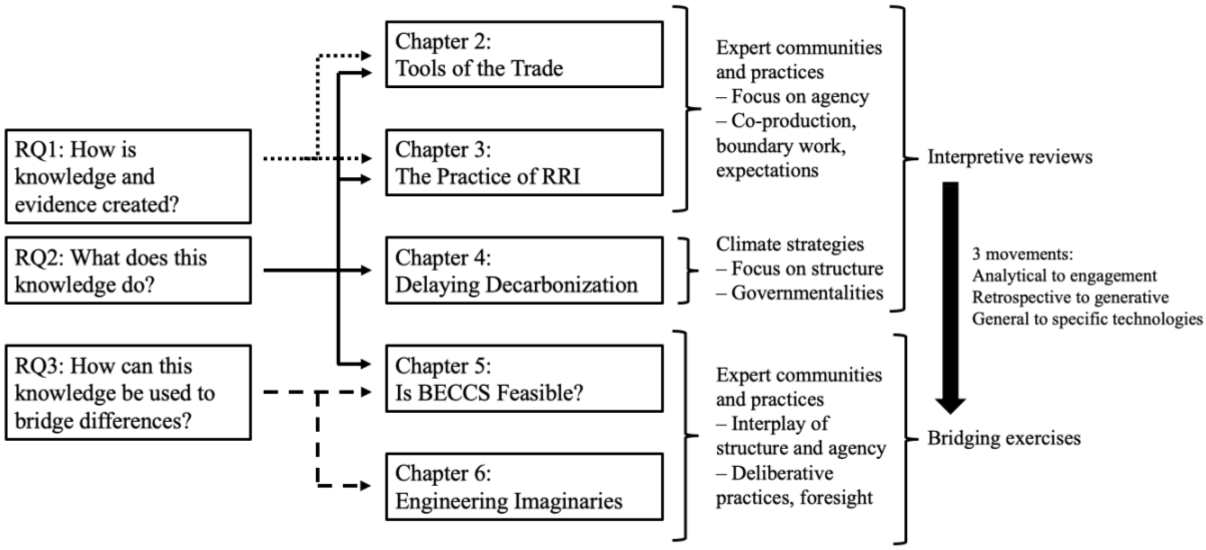
My specific area of inquiry is on the hidden politics of scientific assessment: how knowledge is constructed, contested, and communicated by expert networks, and how these shape understandings of future climate options. I grounded my inquiries in several adjoined literatures: analytical frameworks from science and technology studies (Section 1.4.1) and governmentality studies (Section 1.4.2) deployed in global environmental governance issues, and futurity- and stakeholder-facing activities – described as anticipatory and deliberative – undertaken by technology governance frameworks such as responsible research and innovation (Section 1.4.3).

The research questions parsing this topic: Firstly: How is knowledge and evidence about sunlight reflection and carbon removal created (Chapters 2 and 3)? I focus on scientific expert networks in the global North, and the aims, epistemologies, and effects of their futuring practices. Secondly: What does this knowledge do (Chapters 2, 3, 4, and 5)? I examine how futuring practices set in play resonant terms and frames of reference that actively – if imperfectly – steer climate governance in their image. Thirdly: How can this knowledge be used to bridge differences (Chapters 5 and 6)? I move from understanding how knowledge is constructed to focusing on that construction as a form of experimentation, engaging with expert networks and knowledge types to use futuring practices as platforms exploring directions for research and policy.

The chapters represented three directions. The first was from analytical to engagement work, using critical mappings of the knowledge economy to contextualize and inform bridging activities amongst experts and stakeholders. The second was from retrospective to generative work – from analysis of how knowledge is constructed, to activities that used the future as a sandbox to generate new knowledge, and that has in turn shaped assessments. The final direction went from general technological categories to specific approaches, which engaged with the wider politics of planetary interventions, and then with those of particular approaches and their associated expert networks.

I began with a pair of interpretive reviews. *Tools of the Trade* (Chapter 2) juxtaposed a 'deductive' (elsewhere in the thesis, I refer to this as mission-oriented) mode of assessment prioritizing actionable evidence for policy audiences against a 'deliberative' mode aiming for open-ended appraisal with diverse stakeholders. *The Practice of Responsible Research and Innovation* (Chapter 3) takes a more critical look at deliberative activities, pointing out that these, by setting themselves up against mission-oriented work, engage in the same implicit and instrumental politics of evidence-making. *Delaying Decarbonization* (Chapter 4) examines the longer and wider arc of climate governance, treating sunlight reflection and carbon removal as sociotechnical strategies that draw on the same political rationales that have informed a host of antecedent strategies, from market mechanisms and carbon capture and storage to shale gas and short-lived climate pollutants. I concluded with a pair of bridging and generative engagements on particular approaches. *Is Bioenergy Carbon Capture and Storage Feasible?* (Chapter 5) engaged members of integrated assessment modeling groups and a multi-disciplinary group of critical experts, and found that perspectives on how the 'feasibility' of novel climate options should be calculated were reflections of perspectives on the current and future role of integrated assessment modeling in climate policy. *Engineering Imaginaries* (Chapter 6) engaged scholars invested in early conversation on the risk profiles and appropriate governance of stratospheric aerosol injection (a planetary form of sunlight reflection) and explored the value of foresight approaches to create mutual learning amongst entrenched perspectives, and to generate governance proposals that might be robust against a wide array of future plausibilities.

Table 1.1 Thesis structure



Column 1 describes the research questions (section 1.3), which underpinned by theoretical literatures in section 1.4. Column 2 lists the chapters. Column 3 and 4 describe the aim and topic addressed, the theoretical literature relied upon, and the method or approach designed to inquire after it (section 1.5).

In what follows, I undertake the traditional objectives of a thesis conclusion. In section 7.2, I reflect on each chapter in light of the research questions, while also examining missed areas of inquiry or failed objectives. Where relevant, I reflect on what I would have done differently if I could have done the study over, or where I desire to take research specific to each chapter in the future. Section 7.3 is a 'bird's eye' extension of 7.2's reflections on answering my research questions – I bring together cumulative and generalizable insights across all the chapters on how future-oriented evidence is constructed in sunlight reflection and carbon removal assessment, the implications for governance, and what research avenues the thesis opens up in deliberative, anticipatory, and reflexive assessments. I conclude in section 7.4 with a reflection on how these themes apply more widely in global environmental assessment and governance.

7.2 Chapter discussion and reflections

7.2.1 Tools of the Trade

This chapter contributes to research questions 1 (How is knowledge created) and 2 (What does this knowledge do). The literature on constitutive influences in assessment has tended to focus on actors (institutions, networks, communities) and discourses (or a range of close kin: arguments, frames, narratives, metaphors). *Tools of the Trade* is – to my knowledge – the first paper in the field to treat disparate research methods, practices, and epistemologies as a collective entry point into how assessment is shaped. Moreover, it treats different research practices as 'co-produced' (Jasanoff, 2004; Miller & Wyborn, 2018). The design and conclusions of assessments are entwined with different – even antagonistic – communities of practices, with diverging assumptions about the future of climate strategy, and the proper relationship between assessment, policy, and civil society in making meaningful decisions about that strategy. The chapter then highlights power dynamics and contestations between two particular modes of research practice – a 'deductive' mode most resonantly reflected by climate and economic modeling and a 'deliberative' mode based on more participatory modes of engagement, each backed by particular expert networks. However, the chapter also keeps an eye on future bridging exercises, emphasizing that however these methods are justified within their original communities of practice, they utilize languages and practices that are all means with which to grapple with the future. This should provide ground for conversation and cross-pollination: similar methods can be employed from different perspectives on the future and how it shapes the present (Muidermann et al., 2020).

The focus, however, on research practice and expert communities as an entry point created blind spots with regard to relevant actors and discourses – the fit between these is not perfect. I was able to hone in upon networks of technical modelers and responsible research and innovation practitioners. But there are actors – mostly outside of formal academic spaces – that I ignored because they were not associated with a particular research practice. Key among these are green NGOs and foundations ferociously opposed to a broad conception of climate engineering. On the opposing side are NGOs and institutes that are bullish on the prospects of environmental technologies or a technologized environment (these remain unassessed). Similarly excluded are industry and innovation actors and discourses (e.g. Buck, 2014; Boettcher, 2019; Boettcher, 2020; Carton, 2019; Sapinski et al., 2020). An invisible constituency is the military, or government planners.

A second shortcoming: in placing primary focus on types of research practice, I also shaded over differences within communities and networks practicing them. For example, I treated technical modeling as a broad epistemology, and made a distinction between the communities investigating stratospheric aerosol injection and bioenergy carbon capture and storage. This is broadly correct, but elides more finely-grained perspectives and intents. Stratospheric aerosol injection modeling – indeed, the entire topic – is driven by a core of personnel at Harvard with a degree of technological optimism (see critiques of Oomen, 2019; McKinnon, 2019), but otherwise contains groups and persons who are vigorously skeptical (e.g. Robock, 2020). Likewise, not all integrated assessment modeling groups have equal visibility and significance (Corbera et al., 2017; Guillemot, 2017; Cointe et al., 2020). Responsible research and innovation practitioners are the subject of my next chapter, and it becomes clear that broadly shared practices around deliberation and anticipation contain important nuances. The point is:

juxtaposing research practices and communities made for a coherent narrative, but one that has to be contextualized by studies of actors and discourses, or by more detailed ethnographies.

7.2.2 The Practice of Responsible Research and Innovation

This chapter likewise contributed to research questions 1 (How is knowledge created) and 2 (What does this knowledge do), honing in on the 'deliberative' mode of futuring and its communities of practice that had been more narratively described in the preceding chapter: practitioners of 'responsible research and innovation'. This filled a necessary gap in the literature. Very few in responsible research and innovation apply its principles (how black-boxed scientific assessments can disguise biases and interests, and how expanding transparency and participation in assessments can create greater buy-in) to the interrogation of their own practice – a pair of exceptions are van Oudheusden (2014) and Ribeiro et al. (2017). What I found was that many practitioners – including myself – are doing exactly what we tend to accuse more instrumental, technologically-optimistic actors and modes of assessment of doing. We are shepherding the terms of reference regarding the means and ends of 'climate engineering' towards definitions (societally-defined), processes (participatory, minimal expert-prefacing, and deliberative), and audiences (non-experts, generally as mini-publics) they deem significant, and that functionally supports their epistemic authority. These are conscious efforts to (re)shape 'de facto' governance. But – and this is slightly worrying – responsible research and innovation practitioners demand more reflection than they practice. Much emphasis is placed on the need for corrective measures to instrumental, mission-oriented assessment. Little was placed on any hidden perversities that the mission of responsible research and innovation itself might embody, either in sunlight reflection and carbon removal conversations, or in emerging technology assessment more broadly. What these might be will have to serve as the basis of future work – it is simply a blind spot, and I must confess to sharing it.

No one has previously done this within sunlight reflection and carbon removal assessment. A functional result has perhaps entrenched what I criticized in the course of the chapter, exemplified by that well-used phrase 'who watches the watchers'. Technical experts may undertake critical explorations of how knowledge is made in their own fields (e.g. Schneider, 1997; Gambhir et al., 2019 regarding integrated assessment modeling), but they do not do so consciously to other fields. It is an interesting privilege of many social sciences and humanities that we see ourselves – by some virtue of our disciplinary aims, trainings, and purviews – capable of understanding and interrogating the worldviews of others, and that this is moreover accepted (if sometimes resented – see Balmer et al., 2015) across academic fields. The specific point is that those of us who are trained to explore the politics of science tend to mostly examine those (technical and technocratic) communities and practices with which we disagree, and rarely ourselves (for similar points, see van Oudheusden, 2014 and Delvenne & Parotte, 2018). This has reinforced a partial depiction of the knowledge economy.

At the same time, I was punching with kid gloves, especially in comparison to how modelers and technical experts, or perceived technophiles and instrumentalists, have been interrogated. Owen, 2014, Flegal, 2018, and McKinnon, 2019, for example, deliver much more strongly worded treatments of mission-oriented assessments in stratospheric aerosol injection. Part of this was due to format and venue. The chapter was published as an advanced review in *WIREs Climate Change*, part of a constellation of journals dedicated primarily to big-picture summaries. As such, I was balancing three demands I believed relevant: a meta-analysis of previous works, a lay-ethnography, and practical prescriptions for future work. This chapter was not a detailed ethnography, and could not possibly have been. And even so, the exercise at times felt weirdly insular: I was researching researchers who research researchers.

But this perhaps speaks more to the difficulties of positionality. Responsible research and innovation speaks to the political projects of activist strands of global environmental governance, the critical tradition of science and technology studies and its action-oriented branches, and – for a large plurality of practitioners – profound skepticism about the role of sunlight reflection and carbon removal in the carbon economy. Since I align with these movements, writing this review was an exercise in the dilemmas of agitating within one's tribe. At the same time, recalling these experiences became useful in exercises in which I engaged with communities and epistemologies outside of responsible research and innovation practice, and drove a desire to bridge perspectives as much as critique them (*Is Bioenergy Carbon Capture and Storage Feasible*; *Engineering Imaginaries*).

7.2.3 Delaying Decarbonization

This chapter, as the final interpretive review, again relates most clearly to research questions 1 (How is knowledge created) and 2 (What does this knowledge do). However, it also represents a departure from the two preceding chapters, which clearly relate as interrogations of expert communities and research practices with a focus on agency – the epistemologies, biases, and choices of experts. *Delaying Decarbonization*, rather, examines sunlight reflection and carbon removal as the latest in a line of sociotechnical strategies for addressing climate change, and emphasizes the conditioning influences of structure – the enduring power of neoliberal environmentalism – in shaping how these strategies are designed and applied. The chapter also moves from treating conceptions of futures through assessments as instrumental and project-level expectations, to more systemic governmentalities operative at the level of global climate policy over decades. In the grander scheme of this thesis, *Delaying Decarbonization* shows the interplay between these kinds of futuring – both as structural constraint, as well as the choices of expert networks in research and advocacy. A key success of this chapter, in particular responding to research question 2, was to demonstrate how neoliberal environmentalism dependent on fossil fuels creates systemic incentives and opportunities for putting off clean energy transitions. Sunlight reflection and carbon removal follow in the well-worn steps of a range of diverse proposals that have been advertised as 'bridging' strategies (among others) that might buy time for carbon transitions or vulnerable populations, but in turn provide opportunities for avoiding costly, comprehensive decarbonization in the near-term, and thereby entrench the carbon economy.

One reviewer noted that this was an illuminating and useful narrative review, but could also be seen less kindly as a selective and biased analysis (paraphrased, not quoted). To what extent – and again, this goes to positionality – was the paper's design and conclusion unduly deducted from governmentalities that 'fix' or 'lock-in' the carbon economy? We took care through our methodology to install procedures against confirmation bias – data was collected parallel to analysis and continued till information began to repeat itself (theoretical sampling and saturation), and the conclusions reached in data analysis had to be derived independently by both authors (inter-rater reliability). At the same time, it is also clear that no review of this period's array of sociotechnical strategies could be exhaustive. We noted in our conclusion that we did not examine nuclear energy, or renewables, or adaptation strategies; these may have presented alternative logics to our narrative. Another qualification regarding this chapter was our inability – due to constraints of space and coherence – to give due airing to agency, via practical measures for how to overcome governmentalities built around the carbon economy through research and policy guardrails.

7.2.4 Is Bioenergy Carbon Capture and Storage Feasible?

This chapter – the first of the two bridging engagements – responds to research questions 2 (What does this knowledge do) and 3 (How can knowledge bridge differences). In doing so, it exemplifies the thesis' ambition to integrate critical mapping to forward-facing engagement. The study first attempted an interrogation of 'How did bioenergy carbon capture and storage emerge in integrated assessment modeling?', by applying the analytical framework of boundary work – self-serving interpretations of the same terms of reference – to how different expert networks conceive of and calculate the feasibility of novel technologies in climate governance (research question 2). Based on these mappings, it also deployed multiple rounds of survey and interviews towards a reform-minded questioning of how assessment based on integrated assessment modeling is, and should be, connected to climate targets and policy (research question 3).

What I found was that there is no inherent or obvious way to define and calculate feasibility. Crucially, there were two interdisciplinary but nebulously-defined definitions of 'feasibility' as a boundary object. Each way of conceptualizing and calculating feasibility was underpinned by opposing perspectives on the role of integrated assessment models and its community of practice in shaping future climate strategy. Most modelers and some policy practitioners supported the aims of the current mode of modeling practice, arguing that techno-economic criteria provide a useful first cut of assessment of mitigation options for further deliberation amongst publics and policy-makers – and for whose decisions scientists cannot be held responsible ex-ante. For a mixed group of critics, this mode of assessment abdicates responsibility: science does not neutral map but actively shapes what is possible for policy and public deliberation, and calculating feasibility for mitigation options therefore needs to be more clearly attuned to (perverse) political and institutional priorities.

Crucial to these conclusions was boundary work in the proposed shape of reform. Confronted with each other's perspectives, those defensive of modeling work recognized the need for additional perspectives, but tended to frame these as moderate forms of 'reality checks' and clarificatory science communication. Those critical of modeling work tended to support reformations that might more fundamentally re-conceive how other disciplinary and globally diverse types of knowledge are included in mitigation pathway construction. What was at stake in these opposing perspectives was the authority of the integrated assessment modeling community in the broader landscape of climate governance – for their work to continue more-or-less has it has been in the compilation of IPCC assessment report pathways, against reformations that would erode the leading position of techno-economic modeling. Yet, participants demonstrated active engagement with – and the beginnings of mutual understanding of – how they understood feasibility, the responsibility of researchers, and future science-for-policy in IPCC pathways. This can serve as the basis for future collaboration.

This chapter can therefore be read alongside past and recent studies on the knowledge economy of integrated assessment modeling and IPCC assessment (Keepin & Wynne, 1984; Guillemot, 2018; Beck & Mahony, 2018; Cointe et al., 2020; Livingston & Rummukainen, 2020; van Beek et al., 2020), and connected to a wider literature on perspectives between the proper relationship between science and policy (Turnhout et al., 2013; Sundvist et al., 2014). It is also distinct from these other studies in showing *how* the boundary work on 'feasibility' is taking place.

At the same time, assessment of bioenergy carbon capture and storage as part of a wider carbon sinks strategy was – and is – taking place within a concerted policy turn. Hence, this chapter could perhaps have done more to interrogate feasibility calculations of novel climate technologies with more practical intent. I treated 'feasibility' as a function of wider disciplinary trainings and even political interests. At the same time, I could have undertaken greater investigation into the technical, economic, and socio-political dimensions of feasibility, how these are currently incorporated into modeling structures and studies, and how they could be accounted for in the future within or external to integrated assessment modeling. Fortunately, these are currently being explored by a number of concurrent studies (Rickels et al., 2019; Jewell & Cherp, 2019; Forster et al., 2020, Waller et al., 2020).

Three paths of critical investigations of integrated assessment modeling are unfolding: deep ethnographies (e.g. Cointe et al., 2020) and histories (e.g. van Beek et al., 2020), interrogations of technical and societal 'feasibility' (e.g. Forster et al., 2020), or examinations of research practices leading to concrete recommendations for reform of the research-for-policy enterprise, or regulatory science, represented by modeling (Saltelli et al., 2020; Beck & Mahony, 2018; Kowarsch et al., 2016). Could I have done this study again with the benefit of hindsight, given the wealth of movement on the first and second, I would have fully aimed at the third. The chapter already contains strong elements of this, pointing out why ideas of how to reform or improve integrated assessment modeling are tied to different understandings of the ideal role of that work in IPCC mitigation assessments, and touching on concrete steps for bridging these understandings. A sensible extension would be to design a process built around practical and possible next steps, not just understanding the underpinnings of different ideas for reform.

7.2.5 Engineering Imaginaries

This chapter represents the last of this theses' studies, and the second of the bridging engagements – thus responding to research question 3 (How can knowledge bridge differences). Of all the projects I have conducted or participated in the last decade, this remains the most methodologically expansive, intellectually challenging, and representative of the connection between critical mapping of knowledge politics and anticipation towards governance futures.

Engineering Imaginaries was the write-up of a year-long, three-workshop engagement project (Solar Radiation Management Foresight for Governance, or SRM4G). The objective was to bring together a cohort of highly-motivated researchers and policy analysts active in conversations on how to design future governance around sunlight reflection, particularly the high-leverage, planet-scale stratospheric aerosol injection variant. The result – responding to research question 3 – was the engagement of participants with principles of anticipation and deliberation via foresight-based scenarios, emphasizing not only expertise, but imagination and bias, in thinking expansively about the risks of hypothetical climatic strategies – and in turn, encouraging mutual learning in risk assessment and governance. This engagement confronted participants with the 'why' of governance: what is the relevant thing to be governed, and what governance is therefore to be designed around it (e.g. Gupta et al., 2020).

There were three steps to this exploration. The focus on deliberation, and the opportunity to map a range of alternative futures, facilitated mutual learning and expansive thinking on *key risks and uncertainties* in the future of global climate governance, as well as reflection on why these were thought to be significant. These were rich and comprehensive: participants collaborated to generate eight key risks (e.g. the US-China relationship in the next decade), with four qualitatively-described variations on each risk (e.g. 'Happy couple', 'Frenemies', 'Dragon vs. Eagle', and 'Chinese collapse') – see Tables 6.1 and 6.2. Variations of these risk conditions were combined into *four diverse scenarios* posing future contingencies of stratospheric aerosol injection development: (1) multi-polar fragmentation, (2) clandestine programmes confronted by global public unrest, (3) climate emergencies alongside reckless fossil fuel expansion, and – fascinatingly – (4) a global green transition. Participants then *designed governance systems* tailored to containing the threats and harnessing the opportunities posed by each scenario. An emphasis was placed on the arc of development, with detailed relationships and sequencing (and possible contestations) between individual mechanisms at multiple levels as they developed into fuller regimes over time. Under most scenarios, participants believed that robust governance – that might prove capable of handing the fullest range of scenarios – emphasized innovative and diverse arrangements of stakeholder engagement alongside an international scientific assessment body, and stressed the need for informal governance arrangements to build a clear direction of travel towards multilateral arrangements.

Engineering Imaginaries was therefore a testing ground for what an anticipatory and deliberative process might look like if applying insights learned in previous chapters, and exemplifies the movement from wide-ranging critical interrogation of assessment landscapes towards specific constituencies and technologies, and to engaged, reflexive practice. As feedback from participants indicated, the project usefully introduced experimental futurity to a multidisciplinary, oft-antagonistic (professionally, not personally) cohort of early movers in an emerging debate.

This chapter was also representative of my chapters' movements (see Table 1.1) from analysis to engagement, and from retrospective to generative knowledge. It serves as a capstone of the PhD, relying on the backgrounding work of previous chapters. To generate the idea, I had to have inquired after the knowledge politics of future-making in sunlight reflection, particularly after the differences between technical climate modeling and more qualitative, contingency-based scenarios, or analogical comparisons to previous global governance debates (*Tools of the Trade*). To bring in participants, I had to have known what actors or even institutions were deeply engaged and had opposing, resonant views on stratospheric aerosol injection's most relevant potentials (*The Practice of Responsible Research and Innovation*). And to employ the methods, I had to become acquainted with practices of anticipation and deliberation, which introduced me to responsible research and innovation more fully, to foresight practices and gaming in particular, and to individuals who were instrumental to the execution of the project and who remain so in my professional life.

The study's shortcomings are reported in the chapter itself – indeed, the workshops required participants to reflect on the experience and next steps as part of an aim towards reflexivity. However, I note some of those issues here, as they relate more generally to the themes of the thesis.

The first was that it could be difficult to follow how the expertises and biases of the participants led to particular constructions of risk and governance proposals. Granted, the aim here was to develop mutual learning, which requires the 'chaos' element of scrambled thinking, and in-depth deliberation that cannot be easily traced. At the same, these were deeply-invested actors with recorded points-of-view on the state and directionality of stratospheric aerosol injection development, and perhaps more could have been done to trace how prior expertises and biases were reflected in how risks and governance were designed – or better yet, overcome through deliberation. Simply put, what we gained in deliberation, we lost in critical mapping. A direct point of comparison is the bridging exercise in *Is Bioenergy Carbon Capture and Storage Feasible?*, which relied on iterative interview rounds, and was able to clearly map how different perspectives manifested in proposals for future reform.

An issue particularly raised by the more policy-minded of the participants was that the scenarios could seem quite outlandish. Certainly, this is generalizable to all foresight exercises – or anticipatory work in the social sciences. A common response to the nature of 'plausibility' is that scenarios *should* contain credulity-straining elements in order to test the range and robustness of our planning today – one apocryphal interpretation supports 'anything but aliens and asteroids'. But in sunlight and carbon removal assessment, this creativity has led to tensions on the truth-value of scenarios with deliberately rich fictions, and to debate on the appropriate use of foresight as strategic tools (for steering action) or as only as platforms of communication (to reflect and bridge today's biases). Foresight practice has some ready answers: to develop robust responses to a range of 'plausible alternatives'. Responses should be able to credibly and legitimately address risks across divergent futures that can be plausibly imagined. I support these principles – but at the same time, foresight does not have much traction in the formal social sciences, which has residual reservations about qualitatively generating 'evidence' located in the future. But these avenues will require further explication; I return to them in Section 7.3.5.

Another consideration regarding this chapter was its 'global planning' or 'global cockpit' perspective. Participants deliberated on risk and governance from an abstract, externalized position. It is not my intent to demean this approach, which is endemic in research and is useful in developing landscaping assessments. At the same time, participants were unsure of how to make governance practical or palatable to concrete interests, because they were not asked to role-play them – they simply proposed what they thought, as a group of academics based in sustainability and policy institutes in the global North, would be 'best for the world'. One can imagine a variation on this exercise grounded in more situated perspectives – an EU, American, Chinese, and small island state perspective, or an industry or military one, or an institutional or demographic one – in which case, I would have invited a different set of participants fit to purpose.

Finally, a common criticism of engagement exercises is that they have no impact and process beyond publishing their insights. I did not design tie-ins to decision-making because I saw the exercise as a communication platform rather than a strategic tool, and

I saw the audience as the research community, not policy planners. Feedback from participants validated this aim, and *Engineering Imaginaries*, as a foresight exercise in sunlight reflection and carbon removal assessment, has had some trickle-down effects as a template for other foresight-based exercises. At the same time, in a situated (specific to actor or institution) rather than a global planning exercise, I would also have made stronger efforts to feed the conclusions into further deliberations amongst relevant decision-making bodies and networks.

7.3 Cumulative themes and avenues forward

What follows is an extension of section 7.2's chapter-specific discussions of and reflections on the research questions: (1) How knowledge is created, (2) What knowledge does, and (3) How knowledge can bridge differences. Here, I take a big picture view: exploring cumulative and generalizable insights across all the chapters on how future-oriented evidence is constructed, making explicit some politics in representation (who predominates, and who is missing), procedure (who decides and how), epistemology (how they know), and outcome (what is emerging, and what alternatives are foreclosed). In doing so, I show how structures and agencies – reflecting modes of expertise, conceptions of the correct relationship between science and policy, and beliefs on the history and future direction of climate governance – come together to contest how 'legitimate' or 'useful' assessment is crafted, and how climate strategies are thereby shaped. Building on these thematic observations, I also note future directions in research and action.

7.3.1 Boundary work: Defining what matters

There are radically different narratives available about how research has unfolded. I begin with an explanatory concept: the politics embodied by *boundary work*. Boundary work was originally conceptualized as part of the 'demarcation problem', describing efforts to define what is a part of the enterprise of 'science', as opposed to knowledge-making in 'non-science' – society, or religion, or laypersons (Gieryn, 1983). The concept has since been expanded to explore how expert communities define key, common terms of debate – these are 'boundary objects' (Star & Griesemer, 1989) – to reflect what they believe to be properly at stake (e.g. Jasanoff, 1990). The terms of debate can include terminology and technologies, aims, epistemologies, relationships between science and policy, and research and governance activities. In turn, diverse communities and networks of scholars, practitioners, and decision-makers are brought together around the same macro-conversations, but defining them in ways that best align with their disciplinary apparatus, or institutional agendas, or wider interests. Plainly put: We experts set up the questions so that we are ourselves best suited to deliver the answers.

The interpretive reviews of *Tools of the Trade* and *The Practice of Responsible Research and Innovation* deploy boundary work as a tool of analysis regarding research practices and politics. The first review juxtaposes two mutually-reinforcing complexes of objectives, assessment methods, expertise types, communities of practice, resulting projections or imaginings of future deployments and risks, and proposals for appropriate governance. One is a mission-oriented (in the chapter, I call it 'deductive') mode of technical, model-centric, policy-facing assessment that aspires toward regulatory science: an established relationship between research and policy, where each legitimizes the other (Jasanoff, 2004). Research is structured as 'actionable evidence' (Owen, 2014) to more ably fit the perceived demands of policy-makers, reflecting an understanding of governmental processes – rather than civil society – as the relevant audience. The other is a deliberative mode of qualitative, open-ended, society-facing assessment with more skeptical leanings, which I organize under the banner of responsible research and innovation. My second review takes a deeper dive into responsible research and innovation as a set of aims and activities that seeks to erode the terms of debate that mission-oriented work establishes. It re-defines questions of technology performance into questions of legitimacy gleaned from democratic consent, risk dimensions from technical to sociopolitical, and appropriate epistemologies from small-scale impact assessments and modeling to open-ended, qualitative futuring.

Science is clearly politics by other means. Whether implicitly or instrumentally, each mode reduces the other's scope of relevance, their expertises and epistemologies, and their epistemic authority, to define what is at stake. These are efforts to shape 'de facto governance', or the norms of scientific conduct (Rip, 2014; Gupta & Möller, 2018), as well as formal governance mechanisms that build upon scientific assessment. In the same way that the *audience* of 'policy' or 'decision-makers' functions as research justification and rhetorical resource for mission-oriented work, deliberative engagements appeal to 'society' or 'publics' to slow down what they see as permissive, instrumental assessments. *Models* tend to be treated by mission-oriented work as functional truth machines; while responsible research and innovation practitioners treat them as sandboxes for pinpointing the perceived biases of knowledge technocrats. Actors who see greater potential for sunlight reflection and carbon removal highlight facilitative *analogies* that hint at the capacity for global cooperation on critical infrastructure (e.g. dams and satellites); others refer to less optimistic comparisons in weather modification or nuclear power. Mission-oriented work makes a strong *distinction between research and deployment*, and one can establish non-definitive but common-sense thresholds embodied by physical criteria as well as decision points for backchecking. Practitioners informed by responsible research and innovation more often see a thin line between research and later stages, and argue that the idea of deployment influences viability and desirability of earlier stages.

This does not apply only to assessment practices. There are many examples of academic papers and reports written in direct response to each other that establish or re-define authoritative terms. One example is 'responsibility' itself. Harvard personnel cast a 'responsible' stratospheric aerosol injection research programme as one focused on systems engineering, and that creates technical knowledge as a basis for policy deliberations (Keith, 2017), while others refer to the responsible research and innovation agenda of inclusive participation and reflexivity as the relevant criteria by which assessment can be rendered 'responsible' (Stilgoe et al., 2013). The 'moral hazard' – or the potential for sunlight reflection and carbon removal to pose systemic disincentives to reduce emissions – has been explained away as under-evidenced (Reynolds, 2014) or emphasized as a well-known trend in climate governance (*Delaying Decarbonization*, see also McLaren 2016; McLaren & Markusson, 2020). The 'most vulnerable' are invoked with equal passion by stratospheric aerosol injection's proponents and detractors; the former make a moral argument for the capacity to slow the onset of climate risks for vulnerable populations (Horton & Keith, 2016), and the latter argue that stratospheric aerosol injection can only hurt the vulnerable by replicating paths taken by weather modification or by perpetuating the carbon economy (ETC Group, 2010). Even the umbrella term of 'climate engineering' is subject to boundary work. Policy-oriented work increasingly argues that the umbrella term shades over significant differences in objectives, technicalities, politics, and governance, and should be eliminated in favour of individually tailored platforms. For others, the umbrella term encapsulates a scale and intentionality for tackling the warming that we can neither mitigate nor adapt to via previous strategies, or – less optimistically – activities that embody North-South inequities and anthropocentric hubris.

Not all boundary work is so entrenched. There are opportunities for clarification, and even for harmonizing perspectives. The bridging exercises of this thesis expand boundary work into a tool of engagement for cross-disciplinary learning. *Is Bioenergy Carbon Capture and Storage Feasible?* treats 'feasibility' definitions and calculations of bioenergy carbon capture and storage and other emerging climate options as a boundary object between integrated assessment modelers and critical experts with modeling, critical social science, and policy backgrounds. It finds that feasibility is not simply meaningful in and of itself. Rather, feasibility reflects sboth upportive and critical interpretations of how model-calculated mitigation pathways and global climate policy have influenced each other in the past – e.g. regarding the viability of Paris Agreement's 2C and 1.5C targets, or creating room for negative emissions as a strategy – as well as how they should influence each other in the future. 'Feasibility', in other words, is a proxy for the mode of expertise represented by integrated assessment modeling – and questioning this term of debate challenges the authority on which integrated assessment modeling, as a regulatory science, currently stands. At the same time, this chapter showed that modelers and critics were willing to engage deeply with opposing perspectives. Subsequent works show a stronger understanding of how the controversy of bioenergy carbon capture and storage was seen outside of the integrated assessment modeling community (e.g. Roeglj et al., 2018; van Vuuren et al., 2017), and modeler-led projects that communicate modeling practice and incorporate more stakeholders in early stages of project design are ongoing. *Engineering Imaginaries* takes 'risks and benefits' as a boundary object in a deliberative exercise, inviting participants to bring their experiences to create a range of future scenarios against which 'robust' governance proposals could be directed. This exercise was less a mapping exercise of boundary work as the previous chapters; rather, its value was to pose boundary work as a starting condition for expert assessment, and then to scramble it to generate mutual learning and new insights.

7.3.2 The post-Paris policy turn

At the same time, boundary work does not unfold on an equal footing. Research is undergoing *a policy turn*. How sunlight reflection and carbon removal have come to be separately defined, and how their potentials are calculated, reflects their increasingly normalization in debates over global climate strategy. The big picture, curiosity-driven, open-ended, and often ethically-oriented inquiries more common in early 'climate engineering' debates have been largely sidelined. In the past, there were more frequent comparisons and analogies made with initiatives and frameworks of planetary stewardship (e.g. the Anthropocene, eco-modernism, rewilding – see Brand, 2009; Buck, 2014), or hubris in attempts to control regional and global environments (e.g. weather modification - Fleming, 2009; or fixing the nitrogen cycle - Morton, 2015) or to marshal powerful, dual-use technology platforms (e.g. nanotechnology, or nuclear). Climate interventions were treated not simply as strategies tailored to climate governance – to address the intransigencies of reducing global emissions – but as seeds that might spur new moralities and initiatives for planetary management, for good and ill (compare Brand, 2009 to Hamilton, 2013). Early conversations on 'climate engineering' were deliberately structured to welcome diverse disciplines and stakeholders, as well as critical views, and exhibited an unusual sense of self-reflection and unease (e.g. at the 2010 Asilomar Conference, MacCracken et al., 2010).

The means and ends of these approaches are now settling into received wisdoms, with carbon removal legitimized as a kind of mitigation (part of the 'balance of emissions sources and sinks' referenced in Article 6 of the Paris Agreement), and sunlight reflection cycling through framings as a strategy for buying time for carbon transitions, managing risk, protecting the most vulnerable, and catalyzing mitigation. One can see this as a natural transition over the course of a decade and a half of assessment. Questions have been asked and answered, and debate has moved accordingly from 'blue sky' thinking to policy-relevant, technically-oriented questions, and demand has grown from desk and lab work (modeling, or engagements) to pilot projects and small-scale field tests. To use the language of Stirling (2008), perhaps a period of 'opened-up' social appraisal has generated an informative base of knowledge, and concrete societal preferences and policy decisions have by now emerged (see also *The Practice of Responsible Research and Innovation*).

A more critical interpretation is that the policy turn reflects structural pressures as well as choices evident in assessment work. Climate governance is faced with a question of what to do about the climate warming that cannot be avoided through (slower-moving) carbon transitions or adequately adapted to. A related issue: carbon transitions can forestall but not remove long-lasting carbon accumulating in the atmosphere. Many position sunlight reflection and carbon removal as efforts to grapple with these issues. My research highlights a less hopeful structural conditioning: sunlight reflection and carbon removal fit into emerging governance rationalities in fragmented climate governance by – like carbon capture, or shale gas – proposing to 'buy time' for vulnerable populations and for more comprehensive mitigation to scale up, while also providing potential escape routes for carbon-intensive infrastructures (*Delaying Decarbonization;* see also Carton et al., 2020; Lamb et al., 2020; Buck et al., 2020). Moreover, the key impetus for generating the current demand for research on the capacities and risks of carbon removal approaches has come from the reliance of Paris Agreement targets of 2C and 1.5C on bioenergy carbon capture and storage-heavy mitigation pathways published in the Fifth Assessment Report (AR5), fueled by subsequent commitments towards carbon neutrality in 2050. The emergence of bioenergy carbon capture and storage in AR5, in turn, was another confluence of structural pressure and research agency – a combination of political demand for pathways towards ambitious climate goals, and decisions made amongst integrated assessment modeling research groups to include bioenergy carbon capture and storage as an option that fit within their modeling apparatus, acting as both an energy source and as a carbon sink (*Is Bioenergy Carbon Capture and Storage Feasible?*).

Amongst researchers, these structural pressures dovetail with a deliberate – and generally supported – choice to split assessments of carbon removal from sunlight reflection, and even into individual approaches. This disaggregation of 'climate engineering' stems partly from the need to make policy-oriented assessments tailored to various approaches, but there was a second rationale. Technical and social appraisal of sunlight reflection – particularly stratospheric aerosol injection – had predominated for a time over carbon removal; likely because it came advertised as 'cheap, fast, and imperfect'. Stratospheric aerosol injection posed a higher-leverage climate strategy and a more fascinating intellectual puzzle. The result was a voluminous analytical and engagement social science literature on sunlight reflection alone, with critical and even damning treatments – but very little corresponding work on a multitude of terrestrial, marine, and technological carbon removal approaches (*The Practice of Responsible Research and Innovation*). As carbon removal became normalized as a post-Paris climate strategy, researchers saw value in separating it from sunlight reflection's baggage (see also Gupta & Möller, 2018). Sunlight reflection assessment is also reflecting a policy turn, particularly in modeling work. Here, it is perhaps less because sunlight reflection has become accepted as an object of policy-oriented assessment across a broad spectrum of invested researchers – it remains outside mainstream conversations on climate policy, and is not implicated in the Paris Agreement. Rather, the most vocal advocates of the potentials of sunlight reflection remain active, while many vocal critics have either left the 'climate engineering' debate or focused their attentions on carbon removal. We may also be witnessing what the expectations literature describes as part of the cycle of hype, where emerging technologies are initially exaggerated to generate a sense of added value (or danger), and later normalized to incorporate them into established governance processes (Brown et al., 2000; Hansson, 2011).

7.3.3 The growth of mission-oriented assessment

The policy turn facilitates the mode of *mission-oriented assessment* alluded to in section 4.1. The chapters *Tools of the Trade*, *The Practice of Responsible Research and Innovation*, and *Is Bioenergy Carbon Capture and Storage Feasible?* draw out trends and instances in which this mode of assessment privileges climate and economic modeling as futuring tools. These pose cost-effective, optimized, politically-sanitized, 'global planning' schemes as steering visions for implementation, and narrow feasibilities and risks to climatic and techno-economic dimensions rather than towards socio-political contingencies that fit less easily into modeling study designs (see also Low & Honegger, 2020). Such modeling work trends towards 'solutionism' or 'decisionism', where complex societal implications are described in technical terms for incorporation into policy, and planning for immature technologies is driven towards perceptions of long-term controllability and near-term necessity (*Tools of the Trade*; see also Asayama et al., 2019; Voß et al., 2009).

This trend has been particularly true for a kind of stratospheric aerosol injection modeling (and assessment, generally) spearheaded loosely by personnel within the Harvard Geoengineering Research Programme (HGRP), where optimized, 'best case' deployment schemes are argued to provide a realistic 'hypothesis' for policy deliberations (e.g. Keith & Irvine, 2016). There is an observable aspiration towards acquiring the status of a regulatory science. The framing language and objectives of these modeling studies seem geared towards establishing a standardized base of knowledge to anchor decision-making (*Tools of the Trade*; *The Practice of Responsible Research and Innovation*, see also Flegal, 2018; Oomen, 2019) – akin to the status that already exists for integrated assessment modeling groups (the primary vehicle for mapping mitigation pathways for inclusion in IPCC assessment reports). If integrated assessment modeling of bioenergy carbon capture and storage has been accidentally constitutive of global climate policy (ibid), then this HGRP-led brand of stratospheric aerosol injection modeling is deliberately so.

A mission-oriented assessment mode also conditions social science activity (*Tools of the Trade*; *The Practice of Responsible Research and Innovation*). Engagement and policy studies on carbon removal assume rather than question the suite's inevitable or necessary place in future climate strategy. Assessments increasingly engage carbon removal through policy- and industry- facing frameworks that gauge 'barriers to rollout', with an eye to incentivizing pilot projects and further up-scaling. Proposed governance frameworks for carbon removal aim towards sub-state and polycentric arrangements tailored to individual approaches and projects. A representative re-framing is a move from 'responsible research and innovation' to 'responsible incentivization of research, development, demonstration and (hypothetically) deployment' (Bellamy, 2018). I would argue that this mode is more pronounced in sunlight reflection research, where the efforts of invested advocates have become inertial in the absence of catalyzing developments in climate politics. The use of climate modeling to provide optimized schemes for assessing physical risk continues alongside the proposal of governance frameworks with a comparative focus on technology development and deployment (Reynolds, 2019), research programs with a system engineering approach (Keith, 2017), and small-scale field experiments (Dykema et al., 2014).

Mission-oriented work is only part of the story. There is a great deal of deliberative and anticipatory research that highlights the complexity of imagining societal risk and seeks to broaden participation in expert assessment (*The Practice of Responsible Research and Innovation)*. If aspiring regulatory science crafts its procedures and outputs for governmental policy-makers, then the deliberative and anticipatory research appeals to another audience: 'society'. These emphasize that modeling brackets sociopolitical dimensions and entrenches skewed notions of risk, equity and justice (*Tools of the Trade*; see also Flegal & Gupta, 2018); that optimized depictions of sunlight reflection and carbon removal feeds incentives to delay mitigation (*Delaying Decarbonization*; see also McLaren & Markusson, 2020; Low & Honegger, 2020; Carton et al., 2020), and that stakeholders engaged in open-ended deliberation prioritize expansive socio-political concerns over questions of cost and effectiveness highlighted in technical assessments. Moreover, mission-oriented, policy-facing work and deliberative, society-facing work need not be mutually exclusive, and this ground is currently being fruitfully explored in carbon removal governance. Critically-oriented assessment needs to engage with the plausibility of sunlight reflection and carbon removal approaches being brought into play, and can more actively connect interrogations of the knowledge economy with engagements that prioritize missing perspectives, include local or actor-specific contexts over 'benevolent global planning', and actively design policy guardrails and exit strategies to constrain perverse incentives and outcomes that may come with an instrumental attitude towards developing sunlight reflection and carbon removal (*The Practice of Responsible Research and Innovation*).

In the near term, my concern is whether a policy turn creates a lower profile for society-facing work. Modes of evidence production shape the evidence produced, favouring certain perspectives and actors, and in turn structure expectations about what constitutes feasible and desirable courses of action, while foreclosing alternative options (*Tools of the Trade)*. I would argue that there is a closing down of research methods and practices, with climate and economic modeling being prioritized for their historic connections to policy processes, alongside a fact-finding, supplementary mode of public surveying (e.g. Burns et al., 2016). More innovative forms of engagement that angle towards societal engagement and encourage expansive, alternative futuring – for example, creative dialogue forums, foresight, gaming, and fiction – are viewed as having a less relevant fit. An example: As an active participant in the (slow) growth of foresight-based scenario building in sunlight reflection and carbon removal spaces, I observe perceptions of a divide between 'serious scenarios' represented by earth systems and integrated assessment modeling in IPCC processes, and those with the political guesswork of qualitative foresight projects (*Engineering Imaginaries*). Sunlight reflection, in particular, would be taken more seriously if it were incorporated into integrated assessment modeling frameworks and activities.

From my perspective, this appeal to 'serious' futures represents a clearly false dichotomy. Foresight is used extensively in governmental, military, and business planning; modeling contains profoundly fictional scenarios. Yet, the authority held by modeling seems to be widespread and resilient. A more troubling implication is that kinds of modeling are seen as important not necessarily because they are better assessment platforms, but because they are perceived to have more credibility in the science-policy interfaces of climate governance (Heymann & Dahan Delmedico, 2019 in earth systems modeling; Cointe et al., 2020 on integrated assessment modeling). This, in turn, hints at deeper structural issues in future-oriented research. Why is modeling seen as authoritative? Is it the only practical mode of evidence production that can deal with profoundly systemic calculations? Or is it some general awe of numbers, a transference of authority from modeling physical phenomena into social phenomena? Is it that the modern social sciences have lost or never gained a proper language with which to engage 'futures'?

Assessment must also take care not to prematurely close down on stakeholder demographics. But for the efforts of the Solar Radiation Management Governance Initiative (which funds modeling projects and conducts engagement workshops specifically in the developing world, with an eye to the policy turn), the NGO alliance led by the technology watchdog ETC Group (which seeks to de-legitimize 'climate engineering' as a new colonialism impressed upon marginalized demographics by wealthy polluters), and an opaque, modeling-focused research programme in China (www.china-geoengineering.org), sunlight reflection and carbon removal assessment is based almost completely in the global North, and specifically in the US, northern Europe, and perhaps Japan (Biermann & Möller, 2019; Oldham et al., 2014). This reflects structural inequities in research capacity across all areas of climate assessment and governance, which only serves to reinforce perspectives and interests particular to the North (Blicharska et al., 2017; Corbera et al., 2017). We should therefore be doubly wary of treating a policy turn and mission-oriented work as a natural progression of closing down to clear preferences over the course of assessment.

The sum of these assessment trends is troubling: cost effectiveness and technical considerations, optimized schemes as steering visions, a move from scoping assessments to pilots and field demonstrations (*Tools of the Trade*, *The Practice of Responsible Research and Innovation*), and the legitimization of time-buying strategies tied to the interests of neoliberal environmental governance and the stability of the carbon economy (*Delaying Decarbonization*). We are very gradually closing down on the future, rendering these novel carbon sinks and planetary sunshades necessary as climate managing, economy-stabilizing strategies, and with less of the expansive, experimental forethought prevalent in the debate's earlier days.

7.3.4 Deliberation and anticipation: Situated engagements and targeted questioning

But how can these practices of deliberation and anticipation operate within the context of this post-Paris policy turn? We recalled how responsible research and innovation, in aiming towards 'opening up' technology appraisal, grapples less easily with technology debates that are 'closing down' towards clear political commitments. In light of the policy turn, inquiry is becoming more targeted towards 'responsible incentivization' of carbon removal (Bellamy, 2018) and mission-driven work in sunlight reflection (Morrow, 2019). But although policy and industry interests – particularly in carbon removal – are normalizing and increasing, these are only now beginning to grapple with what scaling up different terrestrial and marine-based approaches might mean for future planning towards long-term low-carbon economies. With a greater interest in approach- and project-specific assessment, a host of questions remain open on improving how more localized social and environmental implications are gauged (*Is Bioenergy Carbon Capture and Storage Feasible?*; Waller et al., 2020; Jewell & Cherp, 2019). We need to ensure that carbon removal assessment is not recklessly instrumentalized as yet another way to extend the carbon budget, while providing opportunities for carbon-heavy activities to carry on as usual.

We therefore make a general plea for 'situated' engagements, as a broad descriptor for inquiring after how meaning of climate and environmental governance is made *locally* (*The Practice of Responsible Research and Innovation*). 'Local' has come to connotate nativeness and neighbourhood; we follow the interpretive tradition in expanding it to include shared institutional, cultural, and disciplinary understandings. We intend this as a necessary supplement to the 'global cockpit' or 'global planner' lens often deployed in landscaping assessments, from modeling to foresight scenarios. A situated engagement, then, could foster dialogue with a rural community in Finnish Lapland, biodiversity assessment experts, the fossil fuel extraction industry, the German foreign ministry, or the International Red Cross / Red Crescent. By aiming at situated understandings, we can explore a much richer depth of perspectives and plausible, relevant agendas than if engagements aimed primarily at mini-publics or collections of sectoral representatives. We write: 'a hosting set of structures, worldviews, policy platforms, and political agendas presents a sandbox within which one can pose context-driven but RRI-informed activities, bounding the plurality of imaginaries and stakeholders, and coming down explicitly on the side of embeddedness rather than divorced critique.'

What perspectives, demographics, and knowledge types are underemphasized or missing? It remains accurate to answer 'who is missing' with 'most constituencies outside of northern academia'. There is a nuance here: debates are wider than they are deep. In terms of width: the original debate on 'climate engineering' was deeply interdisciplinary. A policy turn in assessment came later, and does not erase the fact that a wide range of constituencies and perspectives have long been engaged (Blackstock & Low, 2018). But in terms of depth: it is a very small array of Northern expert networks who work dedicatedly on these issues (Oldham et al., 2014; Biermann & Möller, 2019; Oomen, 2019). This also has knock-on effects for surveys and engagements, since these report the early concerns of (mini)publics, NGOs, or representatives from policy and industry close to home.

Meanwhile, emphasizing and generating perspectives from outside the 'Northern expert' or 'Northern (mini)public' archetypes remains constrained by systemic inequities in capacity and issue prioritization. Institutes and demographics in the global South have rightly been called upon to lead discussions (Rahman et al., 2018). At the same time, there is a dilemma. As Buck (2019) notes, the more limited resources of Southern actors require them to focus on relatively pressing issues built around development and adaptation; hence, there are difficulties in introducing sunlight reflection and carbon removal as matters of concern to demographics who did not drive global warming and have lesser capacity – and perhaps responsibility – to provide time-buying or clean-up strategies. As Northern expert networks, we must take the initiative in putting our resources at wider disposal. I particularly recommend the many works of Holly Jean Buck and Duncan McLaren – both focus on unconventional or marginalized actors and perspectives grappling with the climate engineering imaginary, with an eye to aspects of inequity and justice. Andy Parker and the Solar Radiation Management Governance Initiative (www.srmgi.org) go further, marshalling funding for research groups in developing countries to model the effects of stratospheric aerosol injection on their native regions; these studies are now being published, helping fill one of the debate's larger gaps in terms of both modeling expertise and results.

But beyond bridging the obvious geographic and demographic gaps, engagements could also benefit from more specific lines of questioning. I sympathize with arguments often made in responsible research and innovation circles in favour of deliberation underpinned by principles and institutions of global democracy (e.g. Szerczynski et al., 2014; Chilvers & Kearnes, 2019). But comprehensive societal engagement is a long-term enterprise, and in light of the policy turn, we must ask more targeted questions, of more specific actors and institutions, regarding particular approaches, that guard against technological optimism and highlight perverse incentives and potentials. Lemos et al. (2018) warn against understanding co-production for its own sake, and call for such engagements throughout global environmental governance to lean towards generating outcomes, as much as towards opening processes up. More specific to climate engineering conversations, Morrow (2019) argues that justice-focused questioning would be sharpened by grappling with mission-oriented, policy-facing topics, rather than by circumventing it. For example: If the question is how to integrate bioenergy carbon capture and storage into mechanisms seeking co-benefits between local development and carbon offsets, the first constituencies to engage might be experts on how antecedent (carbon sink) projects have worked within the Kyoto flexibility mechanisms (Honegger & Reiner, 2018), as well as perspectives on how those projects have worked on the ground for local communities (Buck, 2016). If the question is how stratospheric aerosol injection might be deployed and contested, a first constituency might be national security planning experts with knowledge of the perspectives of states with deployment capacity and geopolitical clout. Indeed, I see such engagements as a meaningful proxy for some of the most important exercises or interactions of all: those conducted in sensitive government, industry, and military planning contexts, and are therefore hidden from the public eye. It is important for those of us funded by public money to extract or simulate hidden conversations and strategic preferences.

Within this work, there remains room for landscaping questions on the means and ends of strategies built around planetary sunshades or carbon sinks. These include retaining critical understandings of how assessments and policy surrounding climate strategy continue to be compromised by the inertia of the fossil fuel economy. *Delaying Decarbonization* is an exploration of climate and carbon governmentalities, and this would be a literature to tap into further (Leipold et al., 2017; Lovbrand et al., 2020). Governmentality studies tie into situated engagements, as explorations of actors, levels, discourses, rationalities, and practices built around sustaining or subverting the carbon economy. And understanding these dynamics can help us develop financing, technological and policy support (Geden et al., 2019; Cox et al., 2020) that prioritize guardrails against perverse incentives and activities (McLaren et al., 2019). We can also explore what roles might sunlight reflection and carbon removal (not) play as part of holistic plans towards a post-Covid-19 'green economy' (Sovacool et al., 2020) or in the long-term as part of a century of climate risk management and atmospheric decarbonization (Buck, 2019).

7.3.5 Sharing understandings of 'futures'

A great deal of this thesis is devoted to how anticipatory thinking – with a deliberative and reflexive bent – can benefit explorative assessments. But all my chapters show that, in an even more basic, overarching way, the various communities of practice in this thesis still struggle to communicate with each other about futurity. Earlier, I noted the prevalence of boundary work in assessment – the tendency of (expert) communities and networks to define common problems in self-referential ways. In few places is this clearer than how different disciplines grapple with informing planning with future-oriented assessment.

Selin (2014), in writing of recent interest in anticipation, recalls the 'marginalized intellectual community organized as futures studies', where '[a]cross disciplinary gulfs, in a neglected zip code in the academic landscape, scholars … have been asking similar questions about the limits of our knowledge of and for the future.' The future has in the post-WWII period been a province of rigorous planning and questioning for military and government planners, and then for industry as well (Andersson, 2018; Urry, 2016). This traction has extended unevenly within academia, and to all the realms of assessment it touches. Global environmental governance and science and technology studies, where I situate my work, seem more comfortable with treating the future as an object of study (Anderson, 2010; Brown et al., 2000; Granjou et al., 2015), than with generative work that creates experimental futures to inform debate or policy (e.g. Hajer & Pelzer, 2018; Selin, 2008; Vervoort, 2019; Vervoort et al., 2015).

But regarding anticipatory work as built primarily around forecasting and foresight practices is misleading. A great deal of work across the humanities, the social sciences, economics, and the natural sciences is future-oriented (Adam & Groves, 2007; Andersson, 2018; Poli, 2014; Urry, 2016). Within climate (engineering) assessment alone: We have thought experiments and analogies; we extrapolate past trends and systemic understandings onto incoming problem structures; we use large-n surveys and small-n engagements to gauge matters of concern; we deploy earth systems models to forecast climatic trends, and a further array of economic models and foresight to explore alternative futures or plot road-maps; we use 'serious' games and game theory to test strategies and role-play or simulate actors. Extend this outside of expert- and assessment-driven conversations, and we have fiction, video games, and documentaries and movies that have an arguably greater reach, if not sway.

I used to believe that the humanities and social sciences lacked a language with which to engage the future. This is untrue – we have too many of them. Forms of anticipatory work have long been credible within particular fields and disciplines. No one questions the value of the thought experiment in philosophical inquiry, or game theoretical models for gauging state preferences in nuclear weapon deployments. But modern disciplinary siloing has prevented these approaches from being treated as a broad field of anticipatory philosophies and practices in which exchange and learning is possible.

In the foremost, anticipatory assessment has to grapple with a common set of concepts. This does not require us to invent neologisms; rather, we must engage with boundary work and our tribal nuances on the same terms and practices. Throughout this thesis, I have referred to 'futuring' and 'anticipation', but this is because my first engagement in climate engineering was through foresight (Banerjee et al., 2011), and I see value in the language that surround its practice. Would a philosopher call a thought experiment 'futuring' or 'anticipatory'; or a modeler their model? By clarifying meaning-making, we will be able to categorize our aims and practices, and see what siloed methodologies – numerical models, mental models, deliberation frameworks, foresight frameworks – have in common. One wide-ranging account (though impossibly complicated, approaching a theory of everything) is contained in Poli (2014), which forms the founding intent behind efforts to bring communities of futuring practice together in an ongoing conference series on 'Anticipation' (Trento, 2017; London, 2018; Oslo, 2019). This remains a work in progress; in the meantime, there are more practicable and middle-range mappings.

van Vuuren et al. (2012) and Talberg et al. (2018) look at how quantitative and qualitative scenario families in global environmental and geoengineering assessments respectively, comparing approaches in how these are created, and with a focus on intent – for example, if scenarios are explorative (mapping multiple alternatives), or are communication platforms between different perspectives, or reflect a deeply disciplinary knowledge-building (see also *Tools of the Trade*). Turnheim et al. (2015) seek to develop shared concepts across systems modeling, social and policy analyses of sociotechnical transitions, and initiative-based learning (stakeholder- and project-focused situated engagements), with a focus on integrating these methods within a single framework applied to thematic investigations, in order to harness their respective strengths. Muidermann et al. (2020) maps an even wider range anticipatory practices (including all the approaches looked at in my thesis) by intent (strategic and policy planning; building adaptive and preparation capacities; mobilizing diverse knowledge types; interrogating the present knowledge economy), matched against how the future is conceptualized (probable, plausible, plural, and performative).

These unfinished attempts at finding a common futuring language and framework should facilitate cross-community reflection and learning on intents and rationales that underpin the choice of assessment, and from there, insights and recommendations for governance. But perhaps the most exciting opportunity that arises from this kind of mapping and exchange is being able to mix-and-match anticipatory intent and practice. In this thesis, I tend to examine anticipatory practices as deployed within particular communities, from which they derive claims to epistemic authority (*Tools of the Trade*; *The Practice of Responsible Research and Innovation*; *Is Bioenergy Carbon Capture and Storage Feasible*?). Our research practices are tied to our research politics – as I wrote earlier, we experts set up the questions, and the approaches for exploring them, in a way that ensures that we are able to give the answers that matter to the audiences we believe important. But this does not have to be deterministic; anticipation is ripe for cross-pollination.

Modeling is often treated by the social sciences as deductive and technocratic; but participatory and deliberative concepts can be brought into modeling (*Is Bioenergy Carbon Capture and Storage Feasible*?; see also Salter et al., 2010; Kowarsch & Edenhofer, 2015). Foresight and gaming in 'climate engineering' assessment has tended towards critical examination of the knowledge economy; they can also be bent towards strategic and policy planning for carbon sink or sunlight reflection strategies oriented towards climate justice rather than fixing the carbon economy (*Delaying Decarbonization*; *Engineering Imaginaries*). Turnheim et al. (2015) highlights the possibility for integrating multiple approaches in thematic or problem-focused – rather than purposefully disciplinary – inquiries. An example in the climate engineering sphere: an ongoing collaboration between university and think tank researchers in the US and South Africa has brought together science fiction writers, a multidisciplinary group of experts, and modelers in order to generate new scenarios, aiming to integrate socio-political concerns into modeling design, as well as to inform policy (FCEA, 2020). Indeed, through various practices, situated knowledge can be brought more fully into 'global cockpit' environmental assessments (Pulver & Vandeveer, 2009; Kowarsch et al., 2016; Rosa et al., 2017). This last point of especial interest to me going forward – I return to it in the thesis conclusion (section 7.4).

7.3.6 Positionality: The (personal) politics of science

The stakes are high in these spaces of 'knowledge-making for decision-making' (Miller & Wyborn, 2018), where assessment is crafted to generate or forestall future climate strategies. This is not only because climate change is a keystone challenge of our times, but because of the perceived capacity of sunlight reflection and carbon removal to up-end established wisdoms about climate governance, and the deep investment of networks competing to establish potentials and dangers. I count myself among them, and raise a difficult consideration.

This is *positionality* – my own and those of my peers as creators, translators and users of future-oriented evidence, who compete as well as collaborate. Researchers tend to recognize that we conduct politically constitutive and even politically motivated work; both my bridging engagements in *Is Bioenergy Carbon Capture and Storage Feasible*? and *Engineering Imaginaries* bear this out. And those engagements are efforts to interrogate positionality in others. But am I myself a reliable narrator?

I have crafted a narrative about the momentum behind mission-oriented research, and I clearly (if also critically) align with the objectives of responsible research and innovation. But there is also a widely held interpretation that social scientists in sunlight reflection and carbon removal assessments have been excessively concerned with far flung societal imaginings, outstripping facts provided by technical and engineering assessments (e.g. Victor et al., 2013). I have portrayed stratospheric aerosol injection and bioenergy carbon capture and storage as reified artifacts of modeling and their communities of practice (*Tools of the Trade*). But some would argue that IPCC mitigation pathways are full of immature socio-technical systems, many of which – such as kinds of renewable energy – are not questioned by critics (*Is Bioenergy Carbon Capture and Storage Feasible*?). I have argued that modes of futuring shape evidence, depictions of risk, and proposals for governance in their image (*Tools of the Trade*). Others take the matter-of-fact view that futuring processes exist precisely for scoping new options, and that there is nothing wrong with incrementally increasing testing spaces for those new options, provided they pass the requisite governance benchmarks. Finally, I have portrayed approaches less by their diverse technical characteristics and more by their political usages as 'time-buying' mechanisms that could be easily captured by interests in the carbon economy (*Delaying Decarbonization)*. For others, it is precisely those technical characteristics that shape relevant risk profiles, differentiating sunlight reflection from carbon removal, marine cloud brightening from stratospheric aerosol injection, or direct air carbon capture and storage from bioenergy carbon capture and storage.

Establishing positionality, however briefly, is therefore necessary for contextualizing my narrative: I am concerned that the history of global climate governance adequately demonstrates that states and industries have structured targets, procedures, and instruments to be as lenient as possible on their commitments towards deep-lying decarbonization, and their interests in carbon removal and sunlight reflection may be no different. When I first began work on 'climate engineering', my position was that any first engagement with these incoming 'sociotechnical climate strategies' had to be critical. My colleagues have since done much to convince me that these strategies could – under certain conditions – play a helpful and even essential role in avoiding highly damaging climate change (Morrow et al., 2020; Low & Honegger, 2020). I remain convinced that conditions for success are either profoundly ambitious or delusional – they fly in the face of history, and do not seem likely in the near future. At the same time, sunlight reflection and carbon removal are not necessarily doomed to become distractions from decarbonization. Rather, recognizing these constraints and trends gives us a base of knowledge on which to overcome them. Another implication for my thesis design and results comes from a conviction that expert networks wield the most influence over the terms of debate in emerging science and technology fields. I have therefore focused on cases that critically parse their efforts (*Tools of the Trade*, *The Practice of Responsible Research and Innovation*) or attempt to bridge their perspectives (integrated assessment modelers and critics in *Is Bioenergy Carbon Capture and Storage Feasible?*; stratospheric aerosol injection governance experts in *Engineering Imaginaries*). This has been logistically convenient – I have been able to rely on personal networks and 'background knowledge'. But it also has knock-on effects. By emphasizing the importance of expert networks in the global North, I may be entrenching our visibility in the field and playing into structural inequities.

I was given the opportunity to record my personal positionality in a footnote in *The Practice of Responsible Research and Innovation*. But the editing processes for the other four papers treated such efforts as unnecessary. There are common-sense reasons why. Positionality does not fit as well into positivist studies as interpretive ones, and interdisciplinary journals are agnostic. Researchers in general are wary of setting themselves up for accusations of confirmation bias. And rigorous, detailed treatments of positionality can seem self-indulgent. However, honesty about the personal politics of science is a matter of researchers' responsibility, as much as that of tackling urgent challenges, and keeping research and governance open to diverse kinds of knowledge (Stilgoe et al., 2013; Biermann, 2016).

At the same time, this thesis breaks no new theoretical ground on positionality – it is for me a matter of adhering pragmatically to the reflexivity that responsible research and innovation calls for, bounded by study design, journal choice, the peer review process, and a personal lack of imagination. But I can, in closing, use sunlight reflection and carbon removal assessment as a case study for how positionality has been, and could be engaged.

Positionality can firstly be bounded in research design – examples in deliberative engagements and in qualitative research include interview and survey structuring, participant selection, minimizing expert-based 'leading' in deliberative engagements with mini-publics, or independent confirmation of results in statistical, content, and discourse analysis. Literature thereon exists in every discipline.

Stilgoe et al. (2013) – a well-cited exposition of responsible research and innovation principles and practices – describes two further kinds of reflexivity. The first is 'professional self-critique' (ibid). A variety of frameworks – of which responsible research and innovation is only one – exist for reflection on a researcher's power relations vis-à-vis their objects of study, with regard to the study's design, translation, and dissemination. Efforts at outlining positionality – reflections in-built to the study, or annexed positionality statements – are more common in critical and interpretive literatures, but examples in sunlight reflection and carbon removal research are rare. Otherwise, studies across a range of academic disciplines rely on standard efforts to qualify the limits of a study's design and reach, where the researcher's choices are acknowledged but not deeply personalized or interrogated. Efforts to make the researcher themselves the object of inquiry – for example, through autoethnography – remain niche.

I see only a modest need for 'self-critique' to advance beyond this state of affairs. Positionality reflections should be fit to purpose – I have tried to acknowledged my own in moderate detail because my works are conducted in the interpretive tradition, and because radically different takes on the research and governance of 'climate engineering' exist. Otherwise, positionality should be dealt with pre-emptively in research design. Reflections after-the-fact should be pragmatically oriented towards how that study is to be taken up or how similar studies could be designed in the future.

More fruitful avenues exist for the second kind: institutional (Wynne, 1993) or second-order reflexivity (Schuurbiers, 2011). Scrutiny becomes the work of an external agent, and 'a matter of public concern' (Stilgoe et al., 2013). This goes beyond the usual academic enterprise, in which researchers interrogate each other through peer review and publication; or de facto governance (Rip, 2014), where forceful but uncodified conventions shape research practices and directions (Gupta & Möller, 2018). Examples, rather, are of more institutionalised practices, including social scientists embedded amongst their objects of study (e.g. Oomen, 2019, with the Harvard Geoengineering Research Program), codes of conduct for guiding research (e.g the pioneering 'Oxford Principles' of Rayner et al., 2013), or interdisciplinary programmes (the German Priority Programme on Climate Engineering of Kreuter et al., 2020).

Multi- and interdisciplinary programmes based around thematic issues as one of the more operable options for grappling with reflexivity and positionality, which makes what might otherwise be a navel-gazing exercise a matter of collegial questioning. Certainly, one must safeguard against groupthink, or dominant perspectives and personalities. Otherwise, deliberations amongst colleagues and peers under one roof can mitigate antagonism while facilitating regular and rigorous exchange. Moreover, the need to set and achieve common objectives can facilitate constructive critique. The aforementioned German Priority Programme designed several internal retreats that allowed their researchers to exchange views on each others' disciplinary and personal assumptions, and in turn informed the design of joint projects (Kreuter et al., 2020). Even if such programs cannot often be created from scratch, disciplinarily-grounded networks and consortia – for example, modeling inter-comparison projects – can benefit from regular exchange with stakeholder and other disciplines to have their assumptions, approaches, and framings questioned (Saltelli et al., 2020).

7.4 From climate engineering assessment to global environmental governance

In this thesis, I have drawn several thematic conclusions about key areas, and the overall direction, of the knowledge economy in sunlight reflection and carbon removal assessments. The first was on boundary work: political contestations in scientific assessment over the authoritative meanings of key terms, of plausible or even incontrovertible risks and benefits, of relevant audiences and stakeholders, and of appropriate epistemologies and practices of assessment. The second was on the structural conditionings on assessment posed by a 'policy turn' that is increasingly normalizing climate intervention approaches – certainly, carbon removal is part of the Paris Agreement in all but name ('a balance of sources and sinks'). This in turn could be linked to the constraints posed upon climate strategies writ large by the inertia of the carbon economy, in which time-buying and bridging solutions are increasingly sought. The third observation is the strengthening of a mission-oriented mode of assessment that relies disproportionately on technical modeling and criteria of risk assessment – this inadvertently privileges expert networks built around these research practices, and has produced 'best case' projections of implementation that do not adequately reflect (perverse) political motives and contingencies. The fourth is on the need for more situated and targeted engagements, to forestall technological instrumentalism in the post-Paris era. The fifth reflects on the renewed need to develop shared understandings of how to engage with the future across disciplines and communities of practice. Finally, I reflect upon my own positionality, and how my own perspectives and biases may have informed the analyses, engagements, and narrative of the thesis.

In concluding this thesis, I connect these insights – on the hidden politics of scientific assessment, and the value of situated, deliberative, and anticipatory work – to global environmental governance. This requires some extension beyond the content of my chapters, but it is necessary to connect a thesis that has been pragmatically about expert networks in one corner of climate governance to more systemic conversations about global futures.

Engagements are a means to connect local nuance to global assessment, whether these are represented by frameworks like earth system science (Steffen et al., 2020) and governance (Biermann, 2014) or by assessments and scenarios marshalled by international conventions and commissions (Pulver & Vandeveer, 2009). Sunlight reflection and carbon removal – as climate interventions – have been criticized as part of a managerial, economy-friendly, technofix-oriented view of the global environment (Hamilton, 2013; see also Bakker, 2010; Lövbrand et al., 2015; 2020). In literature spearheaded particularly by scholars of science and technology studies, the science-policy interface of global assessments is complicit (Hulme, 2010; Swyngedouw, 2011; Lövbrand et al., 2009; Taylor, 1997), creating a depoliticised earth system science of unrelatable metrics alongside detached, planetary governance concepts and targets (e.g., planetary boundaries, carbon budgets, the Anthropocene) that is more susceptible to elitist tinkering than facilitative of worldwide engagement.

I sympathize with this reading, but remain wary that it runs the risk of missing the forest for the trees. The future of global (environmental and technological) governance does need to be better angled towards local, situated perspectives and practices, and I have consistently supported this point. But in the tone and tenor of critiques of the global, there can be a strange amnesia about the work that global concepts, assessments, and targets have done to create the systemic awareness and activity whose shortfalls we are currently criticizing. I do not believe that global artifacts are unrelatable – perhaps this is anecdotal, but most of my adult choices have in some way been shaped by globalist concepts, from the 'pale blue dot', to 'sustainability', to 'global governance'. I do not believe that sunlight reflection and carbon removal are doomed to remain imaginary manipulations of a complex of global climate modeling and policy – even though that is precisely what they are right now. I do not believe that global governance architectures are systemically, irretrievably compromised by technocratic science or elitist economic interests. More pragmatically, I do not believe that meaningful and coordinated pursuit of global goals is achievable unless we harness the existing ecosystem of institutions built on the multilateral world order (see Lövbrand et al., 2020, who contrasts modern global environmental governance to more radical reconceptualizations). There are many possible globalisms – we can choose a better version.

The need for globally networked assessments, strategies, and institutions is all the more pressing in a world with increasingly fragmented politics over increasingly systemic issues (Biermann, 2020; Biermann & Kim, 2020, eds; Biermann, 2014). The assessment landscape itself needs to be updated: Jabbour and Flachsland (2017), reviewing four decades of global environmental assessments, argue that institutional and architectural capacity has lost pace with the increasingly systemic needs – the 'epistemic and process complexity' – of assessment. Andonova and Mitchell (2010) point this out as a function of 'rescaling', in which modern environmental governance grapples with emerging geographies, demographics, levels, sectors, and issues, as the connections between them messily emerge.

The task is to maintain dialogues between global- and systems- level assessment and visioning on one hand, and situated agendas and knowledge on the other. This has been usefully described by Montana (2020) as the difference between two animating logics in global environmental agreements: making agreements useful for centralized intergovernmental target-setting and coordination (the logic of authority), against using them to coordinate a multiplicity of practices devolved to the locality at which it is most meaningful (the logic of meaning). I intend for bridging this gap to be the task of my future work, and there is much to draw on. For Miller and Erickson (2004), working in Jasanoff's co-production tradition, technocratic assessments reinforce a global order in which the role of publics and democracy is deemphasized; to open up science, then, is part of systemically strengthening the civic sphere. Lemos et al., (2018), also working with co-production, take a more applied and pragmatic reading familiar to practitioners in responsible research and innovation, transdisciplinarity, and technology assessment frameworks: that it is not only improving process (participation, reflexivity) that matters, but outcomes (decision-making, and sustainability transitions goals). Even Steffen et al. (2020), tracing the 'Geosphere'-centered system of models and assessments that produced the 'new science of the Earth', recognize that the next stage of work must turn towards understanding the 'Anthroposphere' through more bottom-up and people-centered approaches than harnessing technological advancements for top-down monitoring and coordination.

The continuing question is how we – as publicly funded expert networks – can build this capacity with the resources at our disposal, connecting participation and agency to overarching science-policy processes in global environmental governance (e.g. Biermann, 2014; Miller & Erickson, 2004; Cash & Moser, 2000). We can increase the diversity of expert types in GEG science-policy interfaces (Kowarsch et al., 2016) and build capacity for public participation in governance issues (Chilvers & Kearnes, 2019) at multiple levels and scales (Cash & Moser, 2000). We can develop global scenarios – in the outlooks and assessments ubiquitously used across the UN ecosystem – to bridge rather than silo governance issues, and nuance 'global planning' with situated understandings of how global goals are seen through the needs and agendas of particular polities (Pulver & Vandeveer, 2009; Bennett et al., 2016; Rosa et al., 2017; Wardropper et al., 2016; van Vuuren et al., 2012). We can bolster frameworks within the UN system that recognize and seek to integrate systemic connections between governance issues (e.g. the Sustainable Development Goals, or the Sendai Framework of the UN Office for Disaster Risk Reduction), or between multiple kinds of knowledge beyond that of the 'earth systems toolkit's' scientific expertise (e.g. the pioneering framework of the Intergovernmental Platform for Biodiversity and Ecosystem Services, or IPBES - see Beck et al., 2014; Diaz et al., 2015; Kok et al., 2017; Rosa et al., 2017; Turnhout et al., 2017).

Indeed, these efforts at the SDGs, IPBES, Paris Agreement, and the Sendai Framework reflect – at least on paper – trends towards a more systemic integration of horizontal (issues, sectors, and polities) and vertical elements (scales and levels) in assessments. There is no clear formal integration of mandates and procedures, and while there is hope that that the exhortatory, intent-oriented language contained in these frameworks can catalyse greater collaboration, there are also fears that entrenched technocracies and state interests will pursue siloed agendas, tinkering with overhead reports and creating gameable targets and projects (e.g. Wisner, 2020). Given this thesis' examinations of sunlight reflection and carbon removal as promises contained in scientific assessments that might delay decarbonization, I am wary that optimistic language can perversely delay rather than catalyse change. How can these efforts be strengthened in incentives and structures, beyond establishing a direction of travel? How can we make *scientific assessment* a central node of earth system governance architectures (Biermann, 2020; Biermann & Kim, 2020, eds)?

This raises a final query. There is a need for more catalytic, alternative futuring – not only regarding 'climate engineering', but climate governance, and global (environmental) governance writ large (Lövbrand et al., 2015; Vervoort et al., 2015). Sunlight reflection and carbon removal have entered into a policy turn, and this has guided much of my investigations and insights. Indeed, dominant conceptions (at least, among experts) have become deliberately mundane – pragmatically tied into trade-offs around buying time for the carbon economy to transition. But is this reflective of wider understandings in global environmental governance that lean towards the technocratic, managerial, and fix-oriented? Scientific assessment, then, must also become a node for generating and reinforcing new global understandings. In the same way that assessments of sunlight reflection and carbon removal reflect some highly political understanding of the climate problem, global scenarios and assessments – what problems and solutions are established – reflect powerful understandings of the future of the human experiment. As Lövbrand et al. (2009) point out, the 'Anthropocene' emerged from practices and concepts of earth system science. A leading role in assessment processes allows us – again, as publicly funded experts – opportunities to spearhead their reform, and in doing so, remake the futures they project, and the benchmarks by which goals are oriented (Biermann, 2016; Lorimer, 2017). Global environmental governance emerged in a networked era – a sense of global problems, institutions, levels, and importantly, possibilities (Lövbrand et al., 2020). As we enter a more fragmented era, what is the role of catalytic visioning? Are we resigned to critical mappings of an imperfect political economy, or are we capable of helping to build processes that generate new concepts of global governance (Leipold et al., 2019)? As Sayer (2009, p.768) writes of the critical social sciences, have we been 'reduced to little more than skepticism coupled with a concern to be reflexive'? Can we build a 'charming Anthropocene' (Buck, 2014)?

Several years ago, I contributed to a special issue in *Earth's Future* that marked ten years since a seminal article (Crutzen, 2006) that is widely perceived to have pushed climate engineering conversations out of the academic periphery. The short perspective I submitted – 'The Futures of Climate Engineering' – laid the foundation for the inquiries that would eventually become this thesis. It seems fitting to now conclude with the same words that concluded that piece: Anticipation 'emphasizes the explorative and critical aspects of future-making; an appropriate approach for an emerging discourse with limited predictive capacity, strong political pressures, and a multitude of possible outcomes. As the next decade of research unfolds, it will be important to recall that exposing tomorrow's landscape is really an investigation of today's politics' (Low, 2017b).

I believe this is still true, and look forward to tomorrow.

Bibliography

Adam, B. & Groves, C. (2007). *Future matters: Action, knowledge, ethics.* Leiden: Brill.

ADVANCE. (n.d.). Stakeholder and expert dialogue. Retrieved from http://www.fp7-advance.eu/content/stakeholder-and-expert-dialogue.

Ajanovic, A. (2010). Biofuels versus food production: Does biofuels production increase food prices? *Energy.* doi:10.1016/j.energy.2010.05.019

Allen, M. R. (2015). Short-lived promise? The science and policy of cumulative and short-lived climate pollutants. *Oxford Martin Policy Paper.*

Anderson, B. (2010). Preemption, precaution, preparedness: Anticipatory action and future geographies. *Progress in Human Geography* 34(6): 777–798

Anderson, K. (2015). Duality in climate science. *Nature Geoscience* 8(12), 898-900.

Anderson, K., & Jewell, J. (2019). Debating the bedrock of climate-change mitigation scenarios. *Nature* 573: 348-349.

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science, 354*(630), 182-183.

Andersson, J. (2018). *The Future of the World: Futurology, futurists, and the struggle for the post-Cold War imagination.* Oxford: Oxford University Press.

Andonova, L. B. & Mitchell, R. (2010). The rescaling of global environmental politics. *Annual Review of Environment and Resources* 35: 255–282

Anselm, J. & Hansson, A. (2014a). An analysis of the geoengineering advocacy discourse in the public debate. *Environmental Humanities* 5: 101-123.

Anselm, J. & Hansson A. (2014b). Battling Promethean dreams and Trojan horses: Revealing the critical discourses of geoengineering. *Energy Research & Social Science* 2: 135-144.

Asayama, S. (2015). Catastrophism toward 'opening up' or 'closing down'? Going beyond the apocalyptic future and geoengineering. *Current Sociology* 63(1): 89-93.

Asayama, S., Sugiyama, M., Ishii, A. & Kosugi, T. (2019). Beyond solutionist science for the Anthropocene: To navigate the contentious atmosphere of solar geoengineering. *The Anthropocene Review* 1-19. DOI: 10.1177/2053019619843678

Asilomar Scientific Organizing Committee (2010). The Asilomar Conference Recommendations on Principles for Research into Climate Engineering Techniques. In: MacCracken, M. (Ed.). Washington DC: Climate Institute.

Aykut, S. C. (2016). Taking a wider view on climate governance: moving beyond the 'iceberg,' the 'elephant,' and the 'forest'. *WIREs Climate Change* 7: 318–328.

Bain, P. G., Milfont, T. L., Kashima, Y., Bilewicz, M., Doron, G., Gardarsdottir, R. B. ... & Saviolidis, N. M. (2015). Co-benefits of addressing climate change can motivate action around the world. *Nature Climate Change* 6: 154-158.

Bakker, K. (2010). The limits of 'neoliberal natures': Debating green neoliberalism. *Progress in Human Geography* 34(6): 715-735.

Balmer, A., Calvert, J., Marris, C. Molyneux-Hodgson, S., Frow, E., Kearnes, M. ... & Martin, P. (2015). Taking roles in interdisciplinary collaborations: Reflections on working in post-ELSI spaces in the UK synthetic biology community. *Science and Technology Studies* 28(3): 3-25.

Banerjee, B., Collins, G., Low, S. & Blackstock, J.J. (2013). *Scenario planning for solar radiation management: Scenario workshop report.* New Haven September 9-10, 2011.

Barben, D., Beck, S., Matzner, N., & Wittstock. F. (n.d.) Responsible Research and Governance at the Science-Policy Nexus of Climate Change. Retrieved from: https://www.spp-climate-engineering.de/index.php/ce-scipol-2.html

Barben, D., Fisher, E., Selin, C., & Guston, D. (2009). Anticipatory governance of nanotechnology: Foresight, engagement, and integration'. In Hackett, E., Lynch, M., & Wajcman, J. (Eds). *The Handbook of Science and Technology Studies*, third ed. Cambridge, MA: MIT Press, pp. 979-1000.

Bäckstrand, K., & Lövbrand, E. (2006). Planting trees to mitigate climate change: Contested discourses of ecological modernization, green governmentality and civic environmentalism. *Global Environmental Politics* 6(1): 50-75.

Bäckstrand, K., & Lövbrand, E. (2016). The Road to Paris: Contending climate governance discourses in the post-Copenhagen era. Journal of Environmental Policy and Planning dx.doi.org/10.1080/1523908X.2016.1150777

Bäckstrand, K., Meadowcroft, J., & Oppenheimer, M. (2011). The politics and policy of carbon capture and storage: Framing and emergent technology. *Global Environmental Change* 21: 275-281.

Beck, M. (2018). Telling stories with models and making policies with stories: An exploration. *Climate Policy* 18(7), 928-941

Beck, M., & Krueger, T. (2016). The epistemic, ethical, and political dimensions of uncertainty in integrated assessment modeling. *Wiley Interdisciplinary Reviews: Climate Change* 7(5): 627-645.

Beck, S., Borie, M., Chilvers, J., Esguerra, A., Heubach, K., Hulme, M. ... & *Görg, C.* (2014). Towards a Reflexive Turn in the Governance of Global Environmental Expertise. The Cases of the IPCC and the IPBES. *GAIA* 23/2: 80 – 87.

Beck, S., & Mahony, M. (2018a). The politics of anticipation: the IPCC and the negative emissions technologies experience. *Global Sustainability 1*(8): 1–8.

Beck, S., & Mahony, M. (2018b). The IPCC and the new map of science and politics. WIREs Climate Change. https://doi.org/10.1002/wcc.547

Bellamy, R. (2016). A sociotechnical framework for governing climate sngineering. *Science, Technology, & Human Values.* 41**:** 135-162.

Bellamy, R. (2018). Incentivize negative emissions responsibly. *Nature Energy* 3: 532-534.

Bellamy, R., Chilvers, J., Vaughan N.E., & Lenton. T.M. (2013). Opening up geoengineering appraisal: Multi-criteria mapping of options for tackling climate change. *Global Environmental Change* 23: 926-937.

Bellamy, R. & Geden, O. (2019). Govern CO_2 removal from the ground up. *Nature Geoscience,* 12**:** 874–876. doi:10.1038/s41561-019-0475-7

Bellamy, R. & Healey, P. (2014). *A Report on the Climate Geoengineering Governance Project Scenarios Workshop (London 13 October 2014).*

Bellamy, R. & Healey, P. (2018). 'Slippery slope' or 'uphill struggle'? Broadening out expert scenarios of climate engineering research and development. *Environmental Science & Policy* 83: 1-10

Bellamy R. & Lezaun, J. (2017). Crafting a public for geoengineering. *Public Understanding of Science* 26: 402-417

Bellamy, R., Lezaun, J., & Palmer, J. (2019). Perceptions of bioenergy capture and storage in different policy scenarios. *Nature Communications* 1-9. https://doi.org/10.1038/s41467-019-08592-5

Bernstein, S. (2001). *The Compromise of Liberal Environmentalism.* New York: Columbia University Press.

Bernstein, S, Betsill, M., Hoffman, M., & Paterson, M. (2010). A tale of two Copenhagens: Carbon markets and climate governance. *Milennium* 39(1): 161-173.
Bernstein, S. & Hoffmann, M. (2019). Climate politics, metaphors and the fractal carbon trap. *Nature Climate Change*. doi.org/10.1038/s41558-019-0618-2
Bernstein, S., Lebow, R. N., Stein J. G. & Weber, S. (2000) God gave physics the easy problems: Adapting social science to an unpredictable world. *European Journal of International Relations* 6(1): 43-76
Bevir, M. & Rhodes, R. A. W. (Eds). (2016). *Routledge handbook of interpretive political science.* New York: Routledge.
Biermann, F. (2014). *Earth System Governance: World Politics in the Anthropocene.* Cambridge MA: The MIT Press.
Biermann, F. (2016). Politics for a New Earth: Governing in the 'Anthropocene'. In Nicholson, S & Jinnah, S. (Eds). *New Earth Politics: Essays from the Anthropocene.* Cambridge, MA: The MIT Press pp. 405-420.
Biermann, F. (2020). The future of 'environmental' policy in the Anthropocene: time for a paradigm shift. *Environmental Politics.* DOI: 10.1080/09644016.2020.1846958
Biermann, F. & Kim, R. E. (Eds). (2020). *Architectures of Earth System Governance.* Cambridge, UK: Cambridge University Press.
Biermann, F. & Möller, I. (2019). Rich man's solution? Climate engineering discourses and the marginalization of the global south. *International Environmental Agreements* 19: 151. https://doi.org/10.1007/s10784-019-09431-0
Biermann, F. & Pattberg, P. (2008). Global Environmental Governance: Taking stock, moving forward. *Annual Review of Environment and Resources* 33: 277-294
Bijker, W. E., Hughes, T. P., and Pinch, T. J. (Eds). (1987). *The social construction of technological systems: New directions in the sociology and history of technology.* Cambridge, MA: The MIT Press.
Blackstock, J. J. & Low, S. (Eds). (2018). *Geoengineering our climate? Ethics, politics, and governance.* London: Earthscan from Routledge.
Blicharska, M., Smithers, R. J., Kuchler, M., Agrawal, G. K., Gutierrez, J. M., Hassanali, A. … & Mikusinski, G. (2017). Steps to overcome the North-South divide in research relevant to climate change policy and practice. *Nature Climate Change* 7: 21-27.
Blum, M., & Lövbrand, E. (2019). The return of carbon offsetting? The discursive legitimation of new market arrangements in the Paris climate regime. *Earth System Governance* 2: 100028.
Bodansky, D. (2013). The who, what, and wherefore of geoengineering governance. *Climatic Change* 121: 539-551.
Bodle, R. & Oberthür, S. (2014). *Options and Proposals for the International Governance of Geoengineering (Report prepared for the German Federal Environment Agency).*
Boettcher, M. (2019). Cracking the code: how discursive structures shape climate engineering research governance. *Environmental Politics*. DOI: 10.1080/09644016.2019.1670987
Boettcher, M. (2020). Coming to GRIPs with NETs discourse: Implications of discursive structures for emerging governance of negative emissions technologies in the UK. *Frontiers in Climate* 2: 595685. doi: 10.3389/fclim.2020.595685
Boettcher, M. (in preparation). *The discursive construction of climate engineering governance.* Doctoral dissertation. Utrecht University.

Boettcher, M., Gabriel, J. & Harnisch, S. (2015). *Scenarios on Stratospheric Albedo Modification in 2013: SPP 1689 Scenario Workshop Report (Hamburg 22-24 March, 2015).*

Boettcher, M., Gabriel, J. & Low, S. (2016). *Solar Radiation Management: Foresight for Governance*. Working Paper, Potsdam: Institute for Advanced Sustainability Studies.

Borup, M., Brown, N., & Konrad, K. & Van Lente, H. (2006). The sociology of expectations in science and technology. *Technology Analysis & Strategic Management* 18: 285-298

Bowerman, N. H. A., Frame, D. J., Huntingdon, C., Lowe, J. A., Smith, S. M., & Allen, M. R. (2013). The role of short-lived climate pollutants in meeting temperature goals. *Nature Climate Change* 3: 1021-1024.

Boyd, E., Corbera, E., & Estrada, M. (2008). UNFCCC negotiations (pre-Kyoto to COP-9): what the process says about the politics of CDM-sinks. *International Environmental Agreements* 8: 95-112.

Brand, S. (2009). *Whole Earth Discipline: An ecopragmatist manifesto.* New York: Viking Press.

Brown, N. & Michael, N. (2003) A Sociology of Expectations: Retrospecting Prospects and Prospecting Retrospects. *Technology Analysis & Strategic Management* 15: 3-18.

Brown, N., Rappert, B. & Webster, A. (Eds). (2000). *Contested Futures: A Sociology of Prospective Techno-science.* Aldershot: Ashgate.

Buck, H. J. (2014). On the Possibilities of a Charming Anthropocene. *Annals of the Association of American Geographers.* DOI: 10.1080/00045608.2014.973005.

Buck, H. J. (2016). Rapid scale up of negative emissions technologies: social barriers and social implications. *Climatic Change* 139: 155-167.

Buck, H. J. (2017). *Who Authors Future Environments? Public engagement with emerging environmental technologies in the Anthropocene.* Doctoral dissertation. Cornell University.

Buck, H. J. (2018a). The politics of negative emissions technologies and decarbonization in rural communities. *Global Sustainability* 1, e2, 1–7.

Buck, H. J. (2018b). Perspectives on solar geoengineering from Finnish Lapland: Local insights on the global imaginary of Arctic geoengineering. *Geoforum* 91: 78-86.

Buck, H. J. (2018c). Village science meets global discourse: the Haida Salmon Restoration Corporation's ocean iron fertilization experiment. In: Blackstock, J.J. & Low, S. (Eds). *Geoengineering Our Climate? Ethics, Politics and Governance.* Routledge: London. 107-112.

Buck, H. J. (2019). *The World After Geoengineering.* New York: Verso Books.

Buck, H.J., Martin, L.J., Geden, O., Kareiva, P., Koslov, L., Krantz, W., Kravitz, B., Noël, J., Parson, E.A., Preston, C.J., Sanchez, D.L., Scarlett, L., Talati, S. (2020). Evaluating the efficacy and equity of environmental stopgap measures. *Nature Sustainability*. doi:10.1038/s41893-020-0497-6.

Bui, M., Adjiman, C., Bardow, A., Anthony, E. J., Boston, A., Brown, S. ... & MacDowell, N. (2018). Carbon capture and storage (CCS): the way forward. *Energy & Environmental Science* 11: 1062.

Burget, M., Bardone, E. & Pedaste, M. (2017). Definitions and conceptual dimensions of responsible research and innovation: a literature review. *Science and Engineering Ethics* 23: 1-19

Burns, E.T., Flegal, J.A., Keith, D.W., Mahajan, A., Tingley, D., & Wagner, G. (2016) What do people think when they think about solar geoengineering? A review of empirical social science literature, and prospects for future research. *Earth's Future* 4: 536-542

Cadman, T., Maraseni, T., Ma, H. O., & Lopez-Casero, F. (2016). Five years of REDD+ governance: The use of market mechanisms as a response to anthropogenic climate change. *Forest Policy and Economics.* dx.doi.org/10.1016/j.forpol.2016.03.008

Cairns, R. (2019). Public perceptions of geoengineering. In: Blackstock, J.J. & Low, S. (Eds). *Geoengineering Our Climate? Ethics, Politics and Governance.* Routledge: London. 56-59.

Cairns, R. & A. Stirling, A. (2014). 'Maintaining planetary systems' or 'concentrating global power?' High stakes in contending framings of climate geoengineering'. *Global Environmental Change* 28: 25-38.

Calel, R. (2016). Carbon markets: a historical overview. *WIRES Climate Change* 4: 107-119.

Callon, M. (1986). Some elements of a sociology of translation: domestication of the scallops and the fishermen of St. Brieuc Bay. In Law, J., (Ed.). *Power, action and belief: a new sociology of knowledge?* 196-233.

Carton, W. (2016). *Fictitious Carbon, Fictitious Change? Environmental Implications of the Commodification of Carbon*. Doctoral dissertation. Lund University.

Carton, W. (2019). 'Fixing' climate change by mortgaging the future: Negative emissions, spatiotemporal fixes, and the political economy of delay. *Antipode* 51(3): 750-769.

Carton, W., Asiyanbi, A., Beck, S., Buck, H.J. & Lund, J.F. (2020). Negative emissions and the long history of carbon removal. Wiley Interdiscipl. Rev. Clim. Change. doi:10.1002/wcc.671.

Carton, W. (n.d.). Negative emissions and the politics of a projected future: Bioenergy with Carbon Capture and Storage (BECCS), political economy, and the responsibilisation of climate research.
Retrieved from: https://portal.research.lu.se/portal/en/projects/negative-emissions-and-the-politics-of-a-projected-future-bioenergy-with-carbon-capture-and-storage-beccs-political-economy-and-the-responsibilisation-of-climate-research(ee995d5a-a693-4205-84a8-600eac70a05e).html

Cash, D. W. & Moser, S. C. (2000). Linking global and local scales: designing dynamic assessment and management processes. *Global Environmental Change* 10: 109-120.

Castree, N. (2016). Geography and the new social contract for global change research. *Transactions of the Institute for British Geographers* 41(3): 328-347.

Ciplet, D., Roberts, J.T., & Khan, M. (2015). *Power in a Warming World: The New Global Politics of Climate Change and the Remaking of Environmental Inequality*. MIT Press, Cambridge, MA.

Ciplet, D., & Roberts, J. T. (2017). Climate Change and the transition to neoliberal environmental governance. *Global Environmental Change* 46: 148-156.

Chhatre, A., Lakhanpal, S., Larson, A. M. Nelson, F., Ojha, H., & Rao, J. (2012). Social safeguards and co-benefits in REDD+: a review of the adjacent possible. *Current Opinion in Environmental Sustainability* 4(6): 654-660.

Chhetri, N., Chong, D., Conca, K., Falk, R., Gillespie, A., Gupta, A... & Nicholson, S. (2018). Governing Solar Radiation Management. Washington, DC: Forum for Climate Engineering Assessment, American University.

Chilvers, J. & Kearnes, M. (2019). Remaking participation in science and democracy. *Science, Technology & Human Values* 1-34 DOI: 10.1177/0162243919850885
Chris, R. (2016). *Systems Thinking for Geoengineering Policy*. New York: Routledge.
Clapp, J. & Cohen, M. J. (Eds). (2009). *The global food crisis.* Waterloo: Centre for International Governance Innovation and Wilfred Laurier Press.
Coenen, C. & Simakova, E. (2013). STS Policy Innovations, Technology Assessment and the Governance of Technovisionary Sciences. *Science Technology and Innovation Studies* 9(2): 3-20.
Cohen, M. D., March, J. G., & Olsen, J. P. (1972). A garbage can model of organizational choice. A*dministrative Science Quarterly*, 17(1), 1-25.
Cointe, B., Cassen, C. & Nadaï, A. (2020). Organizing policy-relevant knowledge for climate action: Integrated assessment modeling, the IPCC, and the emergence of a collective expertise on socioeconomic emission scenarios. *Science & Technology Studies.* https://sciencetechnologystudies.journal.fi/forthcoming/view/index (accessed 20 May 2019).
Corner, A., Parkhill, K., Pidgeon, N., & Vaughan, N.E. (2013). 'Messing with Nature? Exploring public perceptions of geoengineering in the UK'. *Global Environmental Change* 23, 938-947.
Corry, O. (2017). The international politics of geoengineering: The feasibility of Plan B for tackling climate change. *Security Dialogue 48*(4): 297–315.
Cox, E. & Edwards, N. R. (2019). Beyond carbon pricing: policy levers for negative emissions technologies. *Climate Policy*. DOI: 10.1080/14693062.2019.1634509
Craik, N. & Moore, N. (2014). *Disclosure-based Governance for Climate Engineering Research.* Centre for International Governance Innovation, CIGI Papers No. 50.
Crutzen, P. J. (2006). Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? *Climatic Change* 77: 211-219.
Dauvergne, P. & Clapp, J. (2016). Researching global environmental politics in the 21st century. *Global Environmental Politics* 16(1): 1-12.
de Saille, S. (2015). Innovating innovation policy: the emergence of 'Responsible Research and Innovation'. *Journal of Responsible Innovation.* 2(2): 152-168.
Delvenne, P. & Parotte, C. Breaking the myth of neutrality: Technologial Assessment has politics, Technologial Assessment as politics. *Technological Forecasting and Social Change* 139: 64-72.
Diaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N. … & Zlatanova, D. (2015). The IPBES Conceptual Framework – connecting nature and people. *Current Opinion in Environmental Sustainabil*ity 14: 1-16.
DIPOL (n.d.) Deep transformation scenarios for informing the climate policy discourse. Retrieved from: https://www.pik-potsdam.de/research/transformation-pathways/projects/dipol/dipol
Dimitrov, R. S. (2010) Inside Copenhagen: the state of climate governance. *Global Environmental Politics* 10(2): 18-24.
Dorsch, M. J. & Flachsland, C. (2017). A polycentric approach to global climate governance. *Global Environmental Politics* 17(2): 45-64.
Doughty, J. (2018) Past forays into SRM field research and implications for future governance. Blackstock, J. J. & Low, S. (Eds). *Geoengineering our climate? Ethics, politics and governance.* London: Earthscan from Routledge pp 100-106.
Dykema, J. A., Keith, D. W., Anderson, J., G. & Weisenstein, D. (2014). Stratospheric controlled perturbation experiment: a small-scale experiment to improve

understanding of the risks of solar geoengineering. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 372, 20140059.
Economist. (2019). Countries look at ways to tinker with Earth's thermostat. March 14. Retrieved from: https://www.economist.com/science-and-technology/2019/03/14/countries-look-at-ways-to-tinker-with-earths-thermostat
Edenhofer, O. & Kowarsch, M. (2015). Cartography of pathways: A new model for environmental policy assessments. *Environmental Science & Policy* 51: 56-64.
Edenhofer, O. & Minx, J. (2014) Mapmakers and Navigators, Facts and Values. *Science* 345: 37-38.
Edwards, P. N. (2010) *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming.* MIT Press, Cambridge, MA
Ellenbeck, S. & Lilliestam, J. (2019). How modelers construct energy costs: Discursive elements in Energy System and Integrated Assessment Models. *Energy Research and Social Science 47*: 69-77.
Eliasch, J. (2008). *Climate change: Financing global forests. The Eliash review.* UK: The Stationary Office Limted.
ETC Group (2010). *Geoengineering: Gambling with GAIA*. Ottawa: The ETC Group.
Falkner, R. (2016). The Paris Agreement and the new logic of international climate politics. *International Affairs* 92(5): 1107-1125.
Feng, K. S., Davis, S. J., Sun, L. X., & Hubacek, K. (2015). Drivers of the US CO2 emissions 1997-2003. *Nature Communications* 6:7714 DOI: 10.1038/ncomms8714
Flegal, J. A. (2018). *The evidentiary politics of the geoengineering imaginary.* Doctoral dissertation. University of California, Berkeley. Retrieved from: https://escholarship.org/uc/item/4887x5kh
Flegal, J. A. & Gupta, A. (2018). Evoking equity as a rationale for solar geoengineering research? Scrutinizing emerging expert visions of equity. *International Environmental Agreements* 18: 45-61.
Fleming, J. R. (2009). *Fixing the sky: the checkered history of weather and climate control.* New York: Columbia University Press.
Forster, J., Vaughan, N. E., Gough, C., Lorenzoni, I., & Chilvers, J. (2020). Mapping feasibilities of greenhouse gas removal: Key issues, gaps, and opening up assessments. *Global Environmental Change* 63 102073.
Forum for Climate Engineering Assessment (FCEA) (n.d.) Civil society meeting report. Retrieved from: http://ceassessment.org/civil-society-meeting-report/
Forum for Climate Engineering Assessment (FCEA) (2020) New scenarios and models for climate engineering. Retrieved from: http://ceassessment.org/new-scenarios-and-models-for-climate-engineering/
Foley R.W., Guston D. & Sarewitz, D. (2018). Towards the Anticipatory Governance of Geoengineering. In: Blackstock, J.J. & Low, S. (Eds.). Geoengineering Our Climate? Ethics, Politics and Governance. Routledge: London. 223-244.
Fridahl, M & Lehtveer, M. (2018). Bioenergy with carbon capture and storage (BECCS). Global potential, investment preferences, and deployment barriers. *Energy Research & Social Science* 42: 155–165. DOI: 10.1016/j.erss.2018.03.019.
Fujimura, J. (2003). 'Future Imaginaries: Genome Scientists as Socio-cultural Entrepreneurs', in Goodman, A, Heath, D. & Lindee, S. (Eds.), *Genetic Nature/Culture: Anthropology and Science beyond the Two-Culture Divide*. Berkeley, CA: University of California Press. 176-199.

Funtowicz. S. O. & Ravetz, J . R. (1993). Science for the post-normal age. *Futures* 25(7): 739-755.
Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., . . . Yamagata, Y. (2014). Betting on negative emissions. *Nature Climate Change, 4*(10), 850-853.
Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., . . . Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters, 13*(6), 063002.
Gabriel, J. & Low, S. (2018) Foresight in Climate Engineering. In: Blackstock, J. & Low, S. (Eds). *Geoengineering our Climate? Ethics, Politics, and Governance.*Routledge, London, pp 218-222.
Gambhir, A., Butnar, I., Li P. H., Smith, P., & Srachan, N. (2019). A review of criticisms of integrated asessemt models and proposed approaches to address these, through the lens of BECCS. *Energies*, 12, 1747; doi:10.3390/en12091747.
Gannon, K. E. & Hulme, M. (2018). Geoengineering at the 'edge of the world': Exploring perceptions of ocean fertilisation through the Haida Salmon Restoration Corporation. *Geography and Environment.* DOI: 10.1002/geo2.54
Geden, O. (2016). The Paris Agreement and the inherent inconsistency of climate policymaking. *Wiley Interdisciplinary Reviews: Climate Change*, *7*(6), 790-97.
Geden, O. (2018). Politically Informed Advice for Climate Action. *Nature Geoscience*, *11*(6), 380-83.
Geden, O. & Beck, S. (2014). Renegotiating the global climate stabilization target. *Nature Climate Change*, *4*(9), 747-48.
Geden, O., Peters, G. P. & Scott, V. (2019). Targeting carbon dioxide removal in the European Union. *Climate Policy* 19(4): 487-494.
Geels, F. W. & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy* 36(3): 299-417.
Gieryn, T. F. (1983). Boundary-Work and the demarcation of science from non-science: strains and interests in professional ideologies of scientists. *American Sociological Review*, *48*(6), 781-795.
Glaser, B. G. & Strauss, A. L. (1967). *The discovery of grounded theory. Strategies for qualitative research.* New York: de Gruyter.
Gough, C., Mabon, L., & Mander, S. (2018). Social and ethical dimension of BECCS. In Gough, C., Thornley, P., Mander, S., Vaughan, N. E. & Lea-Langton, A. (Eds.). *Bioenergy carbon capture and storage: Unlocking negative emissions.* Chichester: Wiley. 251-261.
Granjou, C., Walker, J. & Salazar, J. F. (2017) The politics of anticipation: On knowing and governing environmental futures. *Futures* 92: 5-11.
Grin, J. & Grunwald, A. (2000) *Vision Assessment: Shaping Technology in 21st Century Society.* Springer, Berlin Heidelberg
Grunwald, A. (2004) 'Vision Assessment as a New Element of the FTA Toolbox.' Paper, *EU-US Seminar: New Technology Foresight, Forecasting and Assessment Methods (Seville 13-14 May 2004).*
Grunwald, A. (2013) Techno-visionary Sciences: Challenges to Policy Advice. *Science Technology and Innovation Studies* 9(2): 21-38.
Guillemot, H. (2017). The necessary and inaccessible 1.5 C objective: A turning point in the relations between climate science and politics? In Aykut, S. C., Foyer, J. & Morena, E. (Eds.). *Globalising the climate: COP21 and the climatisation of global debates* (pp. 39–56). London, England: Routledge.

Gunderson, R., Stuart, D., & Petersen, B. (2019). The political economy of geoengineering as Plan B: Technological rationality, moral hazard, and new technology. *New Political Economy* 24(5): 696-715.
Gupta, A., & Möller, I. (2018). De facto governance: How authoritative assessments construct climate engineering as an object of governance. *Environmental Politics*, 27, 1–22.
Gupta, A., Möller, I., Biermann, F., Jinnah, S., Kashwan, P., Mathur, V., Morrow, D. R. & Nicholson, S. (2020). Anticipatory governance of solar geoengineering: Conflicting visions of the future and their links to governance proposals. *Current Opinion in Environmental Sustainability* 45: 1-10.
Gupta, J. (2010). A history of international climate change policy. *WIRES Climate Change* 1: 636-653.
Guston, D. (2014). Understanding anticipatory governance. *Social Studies of Science* 44(2), 218-242.
Haas, P. M. (1992). Introduction: Epistemic communities and international policy coordination. *International Organization* 46(1): 1-35.
Habermas, J. (1984). Theory of Communicative Action—Volume 1: Reason and the Rationalization of Society. Boston, MA: Beacon Press.
Haikola, S., Fridahl, M., & Hansson, A. (2018). Views of BECCS among modelers and policymakers. In M. Fridahl (Ed.), *Bioenergy with carbon capture and storage - From global potentials to domestic realities* (pp. 17-30). Stockholm: Liberal European Forum.
Haikola, S., Hansson, A., & Fridahl, M. (2019). Mapmakers and navigators of political terrain: Expert assessments of epistemological uncertainty in integrated assessment modeling of bioenergy carbon capture and storage. *Futures* 114, 102472.
Haikola, S., Hansson, A., & Anshelm, J. (2019). From polarization to reluctant acceptance–bioenergy with carbon capture and storage (BECCS) and the post-normalization of the climate debate. *Journal of Integrative Environmental Sciences*. doi:10.1080/1943815X.2019.1579740
Hajer, M. (1995). *The Politics of Environmental Discourse: Ecological Modernization and the Policy Process.* London: Oxford University Press.
Hajer, M. & Pelzer, M. (2018). 2050-An energetic odyssey: Understanding techniques of 'futuring' in the transition towards renewable energy. *Energy Research & Social Science* 44: 222-231.
Hajer, M. & Versteeg, W. (2005). A decade of discourse analysis of environmental politics: Achievements, challenges, perspectives. *Journal of Environmental Policy & Planning* 7(3): 175-184.
Hale, B. (2012). The world that would have been: Moral hazard arguments against geoengineering. In Preston, C. (ed). Reflecting sunlight: the ethics of solar radiation management. Lanham MD, Rowman and LittleField.
Hamilton, C. (2013). *Earthmasters: The dawn of the age of climate engineering.* New Haven: Yale University Press.
Hansson, A. (2011). Colonising the future: the case of CCS. In Markusson, N., Shackley, S., & Evar, B. (Eds). *The social dynamics of carbon capture and storage.* London: Routledge. 98-114.
Haraguchi, M., Liu, R., Randhawa, J., Salz, S. … & Yuan, Y. (2015). *Human Intervention in the Earth's Climate: The Governance of Geoengineering in 2025+*. Global Governance Futures, Robert Bosch Foundation Multilateral Dialogues.

Harding, A. & Moreno-Cruz J.B. (2016) Solar geoengineering economics: From incredible to inevitable and half-way back. *Earth's Future* 4: 569-577
Harnisch, S., Uther, S, & Boettcher, M. (2015). 'From 'Go Slow' to Gung Ho'? Climate engineering discourses in the UK, the US, and Germany. *Global Environmental Politics* 15(2): 57-78.
Harvey, D. (1982). *The limits to capital.* Chicago: University of Chicago Press.
Hassan, S. S., Williams, G. A., & Jaiswal, A. K. (2019). Moving towards the second generation of lignocellulosic biorefineries in the EU: Drivers, challenges, and opportunities. *Renewable and Sustainable Energy Reviews* 101: 590-599.
Haszeldine, R. S., Flude, S., Johnson, G., & Scott, V. (2018). Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. *Philosophical Transactions of the Royal Society A* 376: 20160447.
Hayes, D. J. M. (2013). Second-generation biofuels: why they are taking so long? *WIRES Energy and Environment* 2: 304-334.
Hein, J., Guarin, A., Fromme, E., & Pauw, P. (2018). Deforestation and the Paris climate agreement: An assessment of REDD+ in the national climate action plans. *Forest Policy and Economics* 90: 7-11.
Held, D. & Roger, C. (2018). Three models of global climate governance: From Kyoto to Paris and beyond. Global Policy 9(4): 527-537.
Heymann, M. & Dahan Dalmedico, A. (2019). Epistemology and politics in earth system modeling: Historical perspectives. *Journal of Advances in Modeling Earth Systems* 11: 1139-1152.
Heyward, J. C. (2013). Situating and Abandoning Geoengineering: A Typology of Five Responses to Dangerous Climate Change. *Political Science & Politics* 46: 23-27. doi:10.1017/S104909651200143
Heyward, J. C. & Rayner, S. (2013). A curious asymmetry: social science expertise and geoengineering. Climate Geoengineering Governance Working Paper 7.
Hilgartner, S. (2015). Capturing the imaginary: Vanguards, visions and the synthetic biology revolution. In: Hilgartner, S., Miller, C., & Hagendijk, R. (Eds). *Science and Democracy: Making Knowledge and Making Power in the Biosciences and Beyond.* Routledge, Taylor and Francis Group. 33–55.
Himmelsbach, R. (2017). How scientists advising the European Commission on research priorities view climate engineering proposals. *Science and Public Policy* 45 (1): 124–133.
Holz, F., Rickter, P. M., & Egging, R. (2015). A global perspective on the future of natural gas: Resources, trade, and climate constraints. *Review of Environmental Economics and Policy* 0(0): 1-22.
Honegger, M., Sugathapala, K. & Michaelowa, A. (2013) Tacking Climate Change: Where Can the Generic Framework Be Located?' *Carbon and Climate Law Review* 2: 125-135.
Hoppe, R. (2005). Rethinking the science-policy nexus: From knowledge utilization and science technology studies to types of boundary arrangements. *Poiesis & Praxis* 3(3): 199-215.
Horton, J. B. & Keith, D. W. (2016). Solar geoengineering and oblications to the global poor. In Preston, C. J. (ed) Climate justice and geoengineering: Ethics and policy in the atmosphertic Anthropocene. London: Rowman & Littlefield. 79-92.

Horton, J. B. & Reynolds, J. L. (2016). The International Politics of Climate Engineering: A Review and Prospectus for International Relations. *International Studies Review* 18: 438–461
Horton, J.B., Reynolds, J., Buck, H.J., Callies, D., Schäfer, S., Keith, D.W., & Rayner, S. (2018). Solar geoengineering and democracy. *Global Environmental Politics*, 18(3), 5-24.
Howarth, R., Ingraffea, A. & Engelder, T. (2011). Should fracking stop? *Nature* 477: 272-275.
Hubert, A.-M. (2017). Revised Code of Conduct for responsible geoengineering research Calgary: University of Calgary.
Hughes, H. R., & Paterson, M. (2017). Narrowing the climate field: The symbolic power of authors in the IPCCs assessment of mitigation. *Review of Policy Research, 34*(6), 744-66.
Hulme, M. (2010). Problems with making and governing global kinds of knowledge. *Global Environmental Change* 20(4): 558-564.
Hulme, M. (2015). *Can science fix climate change? The case against climate engineering.* Cambridge: Polity Press.
Hulme, M. (2016). 1.5 °C and Climate Research after the Paris Agreement. *Nature Climate Change 6*(3): 222-24.
Hulme, M. & Mahony, M. (2010). Climate Change: What Do We Know about the IPCC? *Progress in Physical Geography*, 34(5), 705-18.
Hunsberger, C., Bolwig, S., Corbera, E. & Creutzig, F. (2014). Livelihood impacts of biofuels crop production: Implications for governance. *Geoforum* 54: 248-260.
Huttunen, S. & Hilden, M. (2013). Framing the controversial: Geoengineering in academic literature. *Science Communication,* 36**:** 3-29.
Huttunen, S., Skyten, E. & Hilden, M. (2014). Emerging policy perspectives on geoengineering: An international comparison. *The Anthropocene Review* 1-19.
IAMC. n.d. *Integrated Assessment Modeling Consortium wiki*. Retrieved from: http://iamcdocumentation.eu/index.php/IAMC_wiki.
ICONICS. n.d. *International Committee On New Integrated Climate Change Assessment Scenarios*. Retrieved from: http://www.iconics-ssp.org
IIASA. n.d. *IAMC AR5 Scenario Database*. Retrieved from: https://tntcat.iiasa.ac.at/AR5DB/dsd?Action=htmlpage&page=about.
IPCC (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri R.K. and Meyer L.A. (Eds.)]. IPCC, Geneva, Switzerland, 151 pp.
IPCC. (2014). *Summary for policymakers. In: Climate Change 2014: Mitigation of Climate Change.* Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, … J.C. Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
IPCC. (2018). *Summary for policymakers. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [V. Masson-Delmotte, P. Zhai, H. O. Poertner, D.

Roberts, J. Skea, P. R. Shukla, . . . T. Waterfield (Eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp.
Ipsos MORI. (2010). Experiment Earth? Report on a Public Dialogue on Geoengineering. Retrieved from: https://goo.gl/YrEspL
Irvine, P. J., Kravitz, B., Lawrence, M. G., & Muri, H. (2016). An overview of the Earth system science of solar geoengineering. *WIRES Climate Change* doi: 10.1002/wcc.423
Jasanoff, S. (1990). *The Fifth Branch: Science advisers as policymakers*. Cambridge, MA: Harvard University Press.
Jasanoff, S. (Ed). (2004). *States of Knowledge: The co-production of science and social order.* New York: Routledge.
Jasanoff, S. (2012). Genealogies of STS. *Social Studies of Science 42*(3): 435-441.
Jasanoff, S. & Kim, S. H. (Eds). (2015). *Dreamscapes of Modernity: Sociotechnical imaginaries and the fabrication of power.* Chicago: University of Chicago Press.
Jasanoff, J. & Kim, S. H. (2015). *Dreamscapes of modernity: Sociotechnical imaginaries and the fabrication of power.* Chicago: University of Chicago Press.
Jewell, J. & Cherp, A. (2019). On the political feasibility of climate change mitigation pathways: Is it too late to keep warming below 1.5C? *WIREs Climate Change* 11: e621.
Jinnah, S. & Nicholson, S. (2019). The hidden politics of climate engineering. *Nature Geoscience* 12: 876-879.
Keepin, B. & Wynne, B. (1984). Technical analysis of IIASA energy scenarios. *Nature*, *312*(5996): 691-95.
Keith, D. W. (2000). Geoengineering the climate: History and prospect. *Annual Review of Energy and the Environment 25*: 245-84.
Keith, D. W. (2017). Toward a responsible solar geoengineering research program. *Issues in Science and Technology* 33(3).
Keith, D. W., Duren, R. & MacMartin. D. G. (2014). Field Experiments on Solar Geoengineering: Report of a Workshop Exploring a Representative Research Portfolio. *Philosophical Transactions of the Royal Society A* 372: 20140175.
Keith, D. W. & Irvine, P. J. (2016). Solar geoengineering could substantially reduce climate risks – A research hypothesis for the next decade. *Earth's Future* 4: 549-559.
Keith, D. W. & MacMartin, D. G. (2015). A temporary, moderate and responsive scenario for solar geoengineering. *Nature Climate Change* 5: 201-206
Keohane, R. O. & Victor, D. G. (2011). The regime complex for climate change. *Perspectives on Politics* 9(1): 7-23.
Khan, M. & Roberts, J.T. (2013). Adaptation and international climate policy. *WIRES Climate Change* 4: 171-189.
Kok, M. T. J., Kok, K., Peterson, G. D., Hill, R., Agard, J., & Carpenter, S. R. (2017). Biodiversity and ecosystem services require IPBES to take novel approach to scenarios. *Sustainability Science 12*(1): 177-181.
Kowarsch, M., Garard, J., Riousset, P., Lenzi, D., Dorsch, M., Knopf, B., Harrs, J-A. & Edenhofer, O. (2016). Scientific assessments to facilitate deliberative policy learning. *Palgrave Communications* 2:16092. DOI: 10.1057/palcomms.2016.92
Kravitz, B., Robock, A., Tilmes, S. et al. (2015) The geoengineering model intercomparison project phase 6 (GeoMIP6): Simulation design and preliminary results. *Geoscientific Model Development* 8: 3379-3392.

Kreuter, J. Matzner, N., Baatz, C., Keller, D. P., Markus, T., Wittstock, F., Bernitt, U. & Mengis, N. (2020). Unveiling assumptions through interdisciplinary scrutiny: Observations from the German Priority Program on Climate Engineering (SPP 1689). *Climatic Change.* https://doi.org/10.1007/s10584-020-02777-4

Kuchler, M. (2014). Sweet dreams (are made of cellulose): Sociotechnical imaginaries of second-generation bioenergy in the global debate. *Ecological Economics* 107: 431-437.

Krüger, T. (2017). Conflicts over carbon capture and storage in international climate governance. *Energy Policy* 100: 58-67.

Lahn, B. (2020). A history of the global carbon budget. *WIREs Climate Change.* DOI: 10.1002/wcc.636

Lamb, W.L., Mattioli, G., Levi, S., Roberts, J.T., Capstick, S., Creutzig, F., Minx, J.C., Müller-Hansen, F., Culhane, T., Steinberger, J.K. (2020). Discourses of climate delay. *Global Sustainability* 3 (e17): 1–5. doi:10.1017/sus.2020.13.

Lang, D. J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., Swilling, M., Thomas, C.J. (2012). Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustainability Science* 7 (S1): 25–43.

Latour, B. (1987). *Science in Action: How to follow scientists and engineers through society.* Cambridge MA: Harvard University Press.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation.* Cambridge: Cambridge University Press.

Lazarus, M., Tempest, K., Klevnäs, P. & Korsbakken, J. I., (2015). Natural Gas: Guardrails for a Potential Climate Bridge. New Climate Economy contributing paper. Stockholm Environment Institute, Stockholm, Sweden, and Seattle, WA, US. Retrieved from: http://newclimateeconomy.report.

Leipold, S., Feindt, P. H., Winkel, G. & Keller, R. (2019). Discourse analysis of environmental policy revisited: traditions, trends, perspectives. *Journal of Environmental Policy & Planning* 21(5): 445-463,

Lempert, R., Groves, D. Popper, S. & Bankes, S (2006). A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios. *Management Science* 52: 514-528.

Lemos, M. C., Arnott, J. C., Ardoin, N. M., Baja, K., Bednarak, A. T., Dewulf, A. ... & Wyborn, C. (2018). To co-produce or not to co-produce. *Nature Sustainability* 1: 722-724.

Lenzi, D. (2019). Deliberating about climate change: The case for 'thinking and nudging'. *Moral Philosophy and Politics*. https://doi.org/10.1515/mopp-2018-0034

Levi, M. (2015). Fracking and the climate debate. *Democracy.* Retrieved from: https://democracyjournal.org/magazine/37/fracking-and-the-climate-debate/

Lin, A. C. (2013). Does geoengineering present a moral hazard? *Ecology Law Quarterly* 40(3): 673-712

Lin, A. C. (2015). The missing pieces of geoengineering governance. *Minnesota Law Review* 100(6): 2509-2576

Linner, B. O. & Wibeck, V. (2015). Dual high stake emerging technologies: A review of the climate engineering research literature. *WIREs Climate Change* 6, 255–268. doi: 10.1002/wcc.333

Livingston, J. E. & Rummukainen, M. (2020). Taking science by surprise: The knowledge politics of the IPCC Special Report on 1.5 degrees. *Environmental Science & Policy* 112: 10-16.

Lloyd, I. D. & Oppenheimer, M. (2014). On the Design of an International Governance Framework for Geoengineering. *Global Environmental Politics* 14(2): 45-63.

Lomax, G., Lenton, T. M., Adeosun, A., & Workman, M. (2015). Investing in negative emissions. *Nature Climate Change* 5: 498-500.

Long, J. C. S. (2017). Coordinated action against climate change: A new world symphony. *Issues in Science and Technology* 33(3).

Long, J. C. S., Rademaker, J. G., Anderson, J. G., Benedick, R. E., Caldeira, K., Chaisson, J., ... & Winickoff, D. E. (2012). *Geoengineering: A National Strategic Plan for Research on the Potential Effectiveness, Feasibility, and Consequences of Climate Remediation Technologies*. Task Force on Climate Remediation Research, Bipartisan Policy Center.

Long, T.B. & Blok, V. (2017). When the going gets tough, the tough get going: towards a new — more critical — engagement with responsible research and innovation in an age of Trump, Brexit, and wider populism. *Journal of Responsible Innovation* 4(1): 64-70.

Lorimer, J. (2017). The Anthropo-scene: A guide for the perplexed. *Social Studies of Science* 47(1): 117-142.

Lövbrand, E., Beck, S., Chilvers, J., Forsyth, T., Hedren, J., Hulme, M., Lidskog, R., & Vasileiadou, E. (2015). Who speaks for the future of Earth? How critical social science can extend the conversation on the Anthropocene. *Global Environmental Change* 32: 211-218.

Lövbrand, E., Mobörk, M. & Söder, R. (2020). The Anthropocene and the geo-political imagination: Re-writing Earth as political space. Earth System Governance doi.org/10.1016/j.esg.2020.100051

Lövbrand, E., Pielke Jr., R & Beck, S. (2011). A democracy paradox in studies of science and technology. *Science, Technology & Human Values* 36(4): 474-496.

Lövbrand, E., Rindefjäll, T., Nordqvist, J. (2009). Closing the legitimacy gap in global environmental governance? Lessons from the emerging CDM market. *Global Environmental Politics* 9(2): 74-100.

Lövbrand, E. & Stripple, J. (2011). Making climate change governable: Accounting for carbon as sinks, credits and personal budgets. *Critical Policy Studies* 5(2): 187-100

Lövbrand, E., Stripple, J. & Wiman, B. (2009). Earth System governmentality: Reflections on science in the Anthropocene. *Global Environmental Change* 19: 7-13.

Low, S. (2017a). Engineering imaginaries: Anticipatory foresight for solar radiation management governance. *Science of the Total Environment* 580: 90-104.

Low, S. (2017b). The futures of climate engineering. *Earth's Future* 5: 67-71.

Low, S. & Boettcher, M. (2020). Delaying decarbonization: Climate governmentalities and sociotechnical strategies from Copenhagen to Paris. *Earth System Governance.* DOI: 10.1016/j.esg.2020.100073

Low, S. & Buck, H.J. (2020). The Practice of Responsible Research and Innovation in 'Climate Engineering'. *WIREs Climate Change* 644. DOI: 10.1002/wcc.644

Low, S. & Honegger, M. (2020). A precautionary assessment of systemic projections and promises in sunlight reflection and carbon removal modeling. *Risk Analysis.* DOI: 10.1111/risa.13565

Low, S. & Schäfer, S. (2019). Tools of the trade: practices and politics of researching the future in climate engineering. *Sustainability Science.* DOI: 10.1007/s11625-019-00692-x

Low, S. & Schäfer, S. (2020). Is bioenergy carbon capture and storage feasible? The contested authority of integrated assessment modeling. *Energy Research & Social Science* 60, 101326.

Luokkanen, M., Huttunen, S., & Hilden, M. (2013). Geoengineering, news media and metaphors: Framing the controversial. *Public Understanding of Science* (online version): 1-16.

Maas, A. & Scheffran, J. (2012) Climate Conflicts 2.0? climate engineering as a challenge for international peace and security. *Security and Peace* 30: 193-200

MacCracken M et al. (2010). *The Asilomar conference recommendations on principles for research into climate engineering techniques.* Washington, DC: Climate Institute.

MacMartin, D. G., Caldeira K., & Keith, D. W. (2014). Solar geoengineering to limit the rate of temperature change. *Philosophical Transactions of the Royal Society A* 372: 20140134.

MacMartin, D. G. & Kravitz, B. (2019). Mission-driven research for stratosheric aerosol geoengineering. *Proceedings of the National Academies of Science* 116(4): 1089-1094.

Macnaghten, P. & Szerszynski, B. (2013). Living the global social experiment: An analysis of public discourse on solar radiation management and its implications for governance. *Global Environmental Change-Human and Policy Dimensions* 23: 465-474

Markusson, N. O., Ginn, F., Ghaleigh, N. S., & Scott, V. (2014). 'In case of emergency press here': framing geoengineering as a response to dangerous climate change. WIRES Climate Change 5: 281-290.

Markusson, N. O., Dahl Gjefson, M., Stephens, J. C. & Tyfield, D. P. (2017). The political economy of technical fixes: The (mis)alignment of clean fossil and political regimes. *Energy Research & Social Science* 23: 1-10.

Markusson, N. O., McLaren D., & Tyfield D. (2018). Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs). *Global Sustainability* 1(10): 1–9.

Markusson, N., Jarvis, A., Szerszynski, B., & Tyfield, D. P. (n.d.) Assessing the mitigation deterrence effects of GGR.
Retrieved from: http://gotw.nerc.ac.uk/list_full.asp?pcode=NE%2FP019838%2F1

Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Edenhofer, O., Stocker, T. F., Field, C. B., . . . Matschoss, P. R. (2011). The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups. *Climatic Change, 108*(4), 675-691.

Matzner, N. & Herrenbrück, R. (2016). Simulating a climate engineering crisis: Climate politics simulated by students in model United Nations. *Simulation & Gaming*. DOI 10.1177/1046878116680513

Mayrhofer, J. P. & Gupta, J. (2016). The science and politics of co-benefits in climate policy. Environmental Science & Policy 57: 22-30.

McClellan, J., Sisco, J., Suarez, B. & Keogh, G. (2011). *Geoengineering Cost Analysis: Final Report AR10-182 (Prepared by Aurora Flight Sciences for The University of Calgary).*

McKinnon, C. (2018). Sleepwalking into lock-in? Avoiding wrongs to future people in the governance of solar radiation management research. *Environmental Politics*. DOI: 10.1080/09644016.2018.1450344

McKinnon, C. (2019). The Panglossian politics of the geoclique. *Critical Review of International Social and Political Philosophy.* DOI: 10.1080/13698230.2020.1694216

McLaren, D. P. (2016). Mitigation deterrence and the 'moral hazard' of solar radiation management. *Earth's Future* 4: 596–602 DOI:10.1002/2016EF000445.
McLaren, D. P. (2017). *Mirror, mirror: Fairness and justice in climate geoengineering*. Doctoral dissertation. Lancaster University.
McLaren, D. P. (2018). Whose climate and whose ethics? Conceptions of justice in solar geoengineering modelling. *Energy Research & Social Science, 44*, 209-221.
McLaren, D. P. & Markusson, N. (2020_. The co-evolution of technological promises, modelling, policies and climate change targets. *Nature Climate Change* 10, 392–397. doi:10.1038/s41558-020-0740-1.
McLaren, D. P., Parkhill, K. A., Corner, A., Vaughan, N. E. & Pidgeon, N. F. (2016). Public conceptions of justice in climate engineering: Evidence from secondary analysis of public deliberation. *Global Environmental Change* 41: 64-73.
McLaren, D. P., Tyfield, D. P., Willis, R., Szerczynski, B., & Markusson, N. O. (2019). Beyond 'Net Zero': A case for separate targets for emissions reduction and negative emissions. *Frontiers in Climate* 1: 4 doi: 10.3389/fclim.2019.00004
McNutt, M., Abdalati, W., Caldeira, K., Doney, S. C., Falkowski, P. G., Fetter, S. ... & Wilcox, J. (2015a). *Climate Intervention: Carbon Dioxide Removal and Reliable Seqestration.* National Research Council of the National Academies. Washington D. C.: The National Academies Press.
McNutt, M., Abdalati, W., Caldeira, K., Doney, S. C., Falkowski, P. G., Fetter, S. ... & Wilcox, J. (2015b). *Climate Intervention: Reflecting Sunlight to Cool Earth.* National Research Council of the National Academies. Washington D. C.: The National Academies Press.
Mercer, A.M., Keith, D.W. and Sharp J.D. (2011). Public understanding of solar radiation management. *Environmental Research Letters* 6: 04400.
Mendler de Suarez, J., Suarez, P., Bachofen, C., Fortugno, N., Goentzel, J., Gonçalves, P., ... & Virji, H. (2012). 'Games for a New Climate: Experiencing the Complexity of Future Risks.' Pardee Center Task Force Report. Boston: The Frederick S. Pardee Center for the Study of the Longer-Range Future, Boston University.
Merton, R. K. (1973). *The Sociology of Science: Theoretical and empirical investigations,* Chicago: University of Chicago Press.
Michaelowa, A., Shishlov, I., & Brescia, D. (2019). Evolution of international carbon markets: lessons for the Paris Agreement. *WIRES Climate Change* 613: 1-24.
Milkoreit, M. (2017). Imaginary politics: Climate change and making the future. *Elementa: Science of the Anthropocene* 5. DOI:10.1525/elementa.249
Milkoreit, M., Low, S., Vargas Escarraman, R. & Blackstock, J.J. (2011). The Global Governance of Geoengineering: Using Red Teaming to explore future Agendas, Coalitions and International Institutions. CEADS Papers Volume 1: Red Teaming.
Millard-Ball, A. (2012). The Tuvalu Syndrome: Can geoengineering solve climate's collective action problem? *Climatic Change* 110: 1047-1066
Miller, C. A. (2004). Climate science and the making of a global political order. In Jasanoff, S. (ed). *States of knowledge: The co-production of science and the social order.* London: Routledge.
Miller, C. A. & Erickson, P. H. (2004). The Politics of Bridging Scales and Epistemologies: Science and Democracy in Global Environmental Governance. In: Berkes, F., Wilbanks, T., Capistrano, D. & Reid, W. (Eds). *Bridging Scales and Knowledge Systems: Concepts and Applications in Ecosystem Assessment.* Washington: Island Press.

Miller C. A. & Wyborn, C. (2018). Co-production in global sustainability: History and theories. *Environmental Science and Policy* 113: 88-95.
Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., . . . del Mar Zamora Dominguez, M. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters, 13*(6), 063001.
Montana, J. (2020). Balancing authority and meaning in global environmental assessment: An analysis of organizational logics and modes in IPBES. *Environmental Science & Policy* 112: 245-253.
Morgan, M. G., Nordhaus. R. R. & Gottlieb, P. (2013). Needed: Research Guidelines for Solar Radiation Management'. *Issues in Science and Technology* Spring 37-44.
Morrow, D. R. (2019). A mission-driven research program on solar geoengineering could promote justice and legitimacy. *Critical Review of International Social and Political Philosophy*. DOI: 10.1080/13698230.2020.1694220
Morrow, D. R. (2017). International governance of climate engineering: A survey of reports on climate engineering, 2009-2015. Forum for Climate Engineering Assessment Working Paper Series: 001. SSRN: 2982392
Morrow, D. R., Thompson, M. S., Anderson, A., Batres, M., Buck, H. J., Dooley, K., Geden, O., Ghosh, A., Low, S., Njamnshi, A., Noel, J., Olufemi, O. T., Talati, S., and Wilcox, J. (2020). Principles for Thinking about Carbon Dioxide Removal in Just Climate Policy. *One Earth*. DOI: 10.1016/j.oneear.2020.07.015
Morton, O. (2015). *The Planet Remade: How geoengineering could change the world.* London: Granta.
Mouffe, C. (2005). *On the Political.* London, UK: Routledge.
Möller, I. (2019). *The emergent politics of geoengineering.* Doctoral dissertation. Lund University.
Muidermann, K., Gupta, A., Vervoort, V. & Biermann, F. (2020). Four approaches to anticipatory climate governance: Different conceptions of the future and implications for the present. *WIREs Climate Change* e673.
Myhre, G., Fuglestvedt, J. S., Berntsen, T. K., & Lund, M. T. (2011). Mitigation of short-lived heating components may lead to unwanted long-term consequences. *Atmospheric Environment* 45: 6103-6106.
Naylor, R. L., Liska, A. J., Burke, M. B., Falcon, W. P., Gaskell, J. C., Rozelle, S. D., & Cassman, K. G. (2007). The Ripple Effect: Biofuels, food security, and the environment. *Environment: Science and Policy for Sustainable Development* 49(9): 30-43.
Nerlich, B. & Jaspal, R. (2012). Metaphors we die by? Geoengineering, metaphors and the argument from catastrophe'. *Metaphor and Symbol* 27(2): 131-147.
Neuber, F., & Ott, K., (2020). The buying time argument within the solar radiation management discourse. *Applied Sciences* 10. doi:10.3390/app10134637.
Newell, P. & Paterson M. (2010). *Climate capitalism: global warming and the transformation of the global economy.* Cambridge: Cambridge University Press.
Newell, R. G. & Raimi, D. (2014). Implications of shale gas for climate change. *Environmental Science and Technology* 48: 8360-8368,
Nicholson, S., Jinnah S., & Gillespie, A. (2018). Solar radiation management: a proposal for immediate polycentric governance. *Climate Policy* 18(3): 322- 334.
Niemeyer, S. (2014). A Defence of (deliberative) Democracy in the Anthropocene. *Ethical Perspectives* 21(1): 15–45.

Nightingale, A. J., Eriksen, S., Taylor, M., Forsyth, T., Pelling, M., Newsham, A. ... & Whitfield (2019). Beyond technical fixes: climate solutions and the great derangement. *Climate and Development* DOI: 10.1080/17565529.2019.1624495

Oels, A. (2005). Rendering climate change governable: From biopower to advanced liberal government? *Journal of Environmental Policy & Planning* 7(3): 185-207.

Okerere, C., Bulkeley, H., & Schroeder, H. (2009). Conceptualizing climate governance beyond the international regime. *Global Environmental Politics* 9(1): 58-78.

Olson, K. H. (2007). The clean development mechanism's contribution to sustainable development: a review of the literature. *Climatic Change* 84: 59-73.

Oldham, P. Szerczynski, B., Stilgoe., J., Brown, C., Eacott, B., & Yuille A. (2014). Mapping the landscape of climate engineering. *Philosophical Transactions of the Royal Society A*. 372: 20140065. http://dx.doi.org/10.1098/rsta.2014.0065

Oomen, J. J. (2018). *Dreaming the Designer Climate: Ways of seeing and imagining climate engineering.* Doctoral dissertation. Ludwig-Maximilians-Universität München.

Owen, R. (2014). Solar radiation management and the governance of hubris. Harrison, R. M. & Hester, R. E. (Eds). *Geoengineering of the Climate System*. Royal Society of Chemistry. 212-248.

Parson, E. A. (2014). Climate Engineering in Global Climate Governance: Implications for Participation and Linkage. *Transnational Environmental Law* 3(1): 89-110.

Parson, E.A. & Keith, D.W. (2013). 'End the Deadlock on Governance of Geoengineering Research.' *Science* 339:1278-1279.

Parker, A. (2014). Governing solar geoengineering research as it leaves the laboratory. *Philosophical Transactions of the Royal Society A* 372: 20140173.

Parthasarathy, S., Avery, C., Hedberg, N., Mannisto, J. & Maguire, M. (2010). A public good? Geoengineering and intellectual property. STPP Working Paper 10-1.

Paterson, M. & P-Laberge, X. (2016). Political economies of climate change. *WIRES Climate Change* 9. https://doi.org/10.1002/wcc.506

Pereira, J.C. (2016). 'Geoengineering, scientific community, and policymakers: A new proposal for the categorization of responses to anthropogenic climate change.' *SAGE Open*. doi.org/10.1177/2158244016628591

Poli, R. (2014). *Introduction to Anticipation Studies.* Cham: Springer.

Policy for research and technological development. (2019). Retrieved from: https://www.europarl.europa.eu/factsheets/en/sheet/66/policy-for-research-and-technological-development

Porter, K. E. & Hulme, M. (2013). The emergence of the geoengineering debate in the UK print media: a frame analysis. *The Geographical Journal* 179**:** 342-355.

Prins, G. & Rayner, S. (2007). Time to ditch Kyoto. *Nature* 449: 973-975.

Pindyck, R. S. (2017) The use and misuse of models for climate policy. *Review of Environmental Economics and Policy* 11: 100-114

Pulver, S. & Vandeveer, S. (2009). 'Thinking about Tomorrows': Scenarios, global environmental politics, and social science scholarship. *Global Environmental Politics* 9(2): 1-14.

Rabitz, F. (2016). Going rogue? Scenario for unilateral geoengineering. *Futures* 84: 98-107.

Rayner, S. (2017). Climate engineering. Responsible Innovation or reckless folly? In Asveld, L., van Dam-Mieras, R, Swierstra,T., Lavrijssen, S., Linse, K., van den

Hoven, J. (Eds.). *Responsible Innovation 3. A European Agenda?* Cham: Springer International Publishing. 113–129.
Rayner, S., Heyward, C., Kruger, T., Pidgeon, N., Redgwell, C. & Savulescu, J. (2013). The Oxford Principles. *Climatic Change* 121**:** 499-512.
Reynolds, J. L. (2014). A critical examination of the climate engineering moral hazard and risk compensation concern. *The Anthropocene Review 2*(2): 174-191. doi:10.1177/2053019614554304
Reynolds, J. L. (2019). *The governance of solar geoengineering: Managing climate change in the Anthropocene.* Cambridge: Cambridge University Press.
Reynolds, J. L., Contreras, J. L., and Sarnoff, J. D. (2017). 'Solar climate engineering and intellectual property: Toward a research commons'. *Minnesota Journal of Law, Science & Technology* 18(1): 1-110.
Ribeiro, B. E., Smith, R. D. J. & Millar, K. (2017). A mobilising concept? Unpacking academic representations of Responsible Research and Innovation. *Science and Engineering Ethics* 23: 81-103.
Ricke, K. L., Moreno-Cruz, J. B., & Caldeira, K. (2013). Strategic incentives for climate geoengineering coalitions to exclude broad participation. *Environmental Research Letters* 8: 014021.
Rickels, W., Merk, C., Reith, F., Keller, D. & Oschlies, A. (2019). (Mis)conceptions about modelling of negative emissions technologies. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/ab3ab4
Rip, A. (2014). The past and future of RRI. *Life Sciences, Society and Policy* 10:17.
Robock, A. (2020). Benefits and risks of stratospheric solar radiation management for climate intervention (geoengineering). *The Bridge*, Spring.
Rogelj, J., Popp, A, Calvin, K. V., Luderer, G., Emmerling, E.... & Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5C. *Nature Climate Change* doi.org/10.1038/s41558-018-0091-3
Rosa, I. M. D., Pereira, H. M., Ferrier, S., Alkemade, R., Acosta, L. A., Akcakaya, R. ... & van Vuuren, D. P. (2017). Multiscale scenarios for nature futures. *Nature Ecology & Evolution* 1: 1416-1419.
Ross, K., Damassa, T., Northrop, E., Waskow, D., Light, A., Fransen, T., & Tankou, A. (2018). *Strengthening Nationally Determined Contributions to catalyze actions that reduce short-lived climate pollutants.* Working paper, World Resources Institute and Oxfam.
Rotolo, D., Hicks, D. & Martin B. R. (2015). What is an Emerging Technology? *Research Policy* 44(10): 1827-1843.
Røttereng, J.-K. S. (2018). The comparative politics of climate change mitigation measures: Who promotes carbon sinks and why? *Global Environmental Politics* 18(1): 52-75.
Rockström, J., Steffen, W., Noone, K., Persson, Å, Chapin, III, F. S., Lambin, E. ... & Foley, J. (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society* 14(2): 32.
Saltelli, A., Bammer, G., Bruno, I., Charters, E., Di Fiore, M., Didier, E. ... & Vineis, P. (2020). Five ways to ensure models serve society: A manifesto. *Nature* 582: 482-484.
Salter, J., Robinson, J., & Wiek, A. (2010). Participatory methods of integrated assessment-a review. *Wiley Interdisciplinary Reviews: Climate Change, 1*(5), 697-717.

Sanders, L. (1997). Against deliberation. *Political Theory* 25(3): 347-376.
Sapinski, J. P., Buck, H. J. & Malm, A. (2020). *Has it come to this? The promises and perils of geoengineering on the brink.* Rutgers University Press.
Sarewitz, D. (2016). Saving Science. *The New Atlantis* Spring/Summer 5-40.
Sayer, A. (2009). Who's afraid of critical social science? *Current Sociology* 57(6): 767-786.
Schäfer, S., Lawrence, M., Stelzer, H., Born, W. & Low, S. (2015). *The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight Away from Earth.* Funded by the European Union's Seventh Framework Programme under Grant Agreement 306993.
Schipper, L. (2006). Conceptual history of adaptation in the UNFCCC process. *Review of European Community and International Environmental Law* 15(1): 82-92.
Schneider, L. (2009). Assessing the additionality of CDM projects: practical experiences and lessons learned. *Climate Policy* 9(3): 242-254.
Scholte, S., Vasileiadou, E. & Petersen, A.C. (2013). 'Opening up the societal debate on climate engineering: How newspaper frames are changing'. *Journal of Integrative Environmental Sciences* 10(1): 1-16.
Schot, J., & Rip, A. (1997). The past and the future of constructive technology assessment. *Technological Forecasting and Social Change* 54(2-3): 251-268.
Schrag,D. P. (2012). Is shale gas good for climate change? *Daedalus* 2: 72-80.
Schubert, J. (2019). Measuring, modelling, controlling the climate? Numerical expertise in U.S. climate engineering politics. In Prutsch, M. J. (Ed). *Science, Numbers and Politics.* Cham: Palgrave MacMillan. 181-202.
Schuurbiers, D. (2011). What happens in the lab does not stay in the lab: Applying midstream modulation to enhance critical reflection in the laboratory. *Science and Engineering Ethics* 17(4): 769-788.
Scott, V., Gilfillan, S., Markusson, N., Chalmers, H., & Haszeldine, R. S. (2012). Last chance for carbon capture & storage. Nature Climate Change. DOI: 10.1038/NCLIMATE1695
SENSES. (n.d.) The new generation of climate change scenarios. Retrieved from: http://senses-project.org
Selin, C. (2008). The sociology of the future: Tracing stories of technology and time. *Sociology Compass* 2/6: 1878-1895.
Shackley, S., & Wynne, B. (1996). Representing uncertainty in global climate change science and policy: boundary-ordering devices and authority. *Science, Technology, & Human Values* 2(3): 275-302.
Shearer, C. Bistline., J, Inman, M., & Davis, S. J. (2014). The effect of natural gas supply on US renewable energy and CO2 emissions. *Environmental Research Letters* 9: 094008.
Shepherd, J., Caldeira, K., Cox, P., Haigh, J., Keith, D.W., Launder, B.... & Watson, A. (2009). *Geoengineering the climate: science, governance and uncertainty*. London: The Royal Society.
Shindell, J., Kuylenstierna, J. C. I., Vignati, E., van Dingenen, R., Amann, M, Klimont Z. ... & Fowler, D. Simultaneously mitigating near-term climate change and improving human health and food security. *Science* 13: 183-189.
Shindell, J., Borgford-Parnell, N., Brauer, M., Kuylenstierna, J. C. I., Leonard, S.A., Ramanathan, V. ... & Srivastava, L. (2017). A climate policy pathway for near- and long-term benefits. *Science* 356: 493-494.

Shoemaker, J. K., Schrag, D. P., Molina, M. J., & Ramanathan, V. (2013). What role for short-lived climate pollutants in mitigation policy? *Science* 342: 1323-1324.
Sillmann, J., Lenton, T. M., Levermann, A., Ott, K., Hulme, M., Benduhn, F. & Horton, J. B. (2015). Climate emergencies do not justify engineering the climate. *Nature Climate Change* 5: 290-292.
Sismondo, S. (2008). Science and technology studies and an engaged program. In E. Hackett, O. Amsterdamska, M. Lynch, & J. Wajcman (Eds). *The handbook of science and technology studies* Cambridge, MA: MIT Press. pp. 13–30.
Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., . . . Yongsung, C. (2015). Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change 6*(1): 42-50.
Smith, W. & Wagner, G., 2018. Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. *Environ. Res. Lett.* 13 (124001). doi:10.1088/1748-9326/aae98d.
Sovacool, B., Furszyfer Del Rio, D. & Griffiths, S. (2020). Contextualizing the Covid-19 pandemic for a carbon constrained world: Insights for sustainability transitions, energy justice, and research methodology. *Energy Research & Social Science* 68: 101701.
Sovacool, B. & Hess, D. J. (2017). Ordering theories: Typologies and conceptual frameworks for sociotechnical change. *Social Studies of Science* 47(5): 703-750.
Sovacool, B., Hess, D. J., Amir, S., Geels, F. W., Hirsh, R., Rodriguez Medina, L. … & Yearley, S. (2017). Sociotechnical agendas: Reviewing future directions for energy and climate research. *Energy Research & Social Science* 70: 101617.
Star, S. L., & Griesemer, J. R. (1989). Institutional ecology, `translations and boundary objects: amateurs and professionals in Berkeley's museum of vertebrate zoology, 1907-39. *Social Studies of Science 19*(3): 387-420.
Steffen, W., Richardson, K., Rockström, J., Schellnhuber, H. J., Dube, O. P., Dutreuil, S., Lenton, T. M. & Lubchenko, J. (2020). The emergence and evolution of Earth System Science. *Nature Reviews* 1: 54-63.
Stephens, J.C. & Surprise, K. (2020). The hidden injustices of advancing solar geoengineering research. *Global Sustainability* 3(2): 1–6. https://doi.org/10.1017/sus.2019.28
Stilgoe, J. (2015). *Experiment Earth: Responsible innovation in geoengineering.* New York: Routledge.
Stilgoe, J., Owen, R. & Macnaghten, P. (2013). Developing a framework for responsible innovation'. *Research Policy* 42: 1568-1580.
Stirling, A. (2008). "Opening up' and 'closing down': Power, participation, and pluralism in the social appraisal of technology.' *Science, Technology and Human Values* 33: 262 – 294.
Stripple, J. & Bulkeley H. (Eds). (2014). *Governing the climate: New approaches to rationality, power and politics.* Cambridge: Cambridge University Press.
Suarez, P. & van Aalst, M. K. (2017). Geoengineering: A humanitarian concern. *Earth's Future* 5: 183–195. doi:10.1002/2016EF000464.
Sugiyama, M., Asayama, S., Kosugi, T., Ishii, A., Emori, S., Adachi, J., … & Yoshizawa, G. (2017). *Sustainability Science* 12: 31-44. DOI 10.1007/s11625-016-0376-2
Sundqvist, G., Gasper, D., St. Clair, A. L., Erlend, A. S., Hermansen, A. T., Yearly, S., … Wynne, B. (2018). One world or two? Science-policy interactions in the climate field. *Critical Policy Studies* 12(4): 448-468.

Surprise, K. (2019). Preempting the second contradiction: Solar geoengineering as spatiotemporal fix. *Annals of the American Association of Geographers* 108(5): 1228-1244.
Sweeney, J. A. (2014). Command-and-control: Alternative futures of geoengineering in an age of global weirding. *Futures* 57: 1-13.
Swyngedouw, E. (2011). Depoliticized Environments: The end of nature, climate change and the post-political condition. *Royal Institute of Philosophy Supplement* 69: 253-274.
Talberg A., Thomas S., Christoff P., & Karoly, D. (2018). How geoengineering scenarios frame assumptions and create expectations. *Sustainability Science* 1-12
Tavoni, M., & Socolow, R. (2013). Modeling meets science and technology: an introduction to a special issue on negative emissions. *Climatic Change 118*(1): 1-14.
Tavoni, M. & Tol, R. S. J. (2010). Counting only the hits? The risk of underestimating the costs of stringent climate policy. *Climatic Change 100*(3-4): 769-78.
Taylor, P. J. (1997). How do we know we have global environmental problems? Undifferentiated science-politics and its potential reconstruction. In: Taylor, P. J., Halfon, S., & Edwards, P. *Changing Life: Genomes-Ecologies-Bodies-Commodities.* Minneapolis: University of Minnesota Press pp. 149-174.
Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L. ... & Williams, R. (2009). Beneficial biofuels: The food, energy, and environment trilemma. *Policy Forum* 325: 270-271.
Tour, J. M., Kittrell, C., & Colvin, V. L. (2010). Green carbon as a bridge to renewable energy. *Nature Materials* 9: 871-874.
Turnheim, B., Berkhout, F., Geels, F. W., Hof, A., McMeekin, A., Nykvist, B. & van Vuuren, D. P. (2015). Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Global Environmental Change* 35: 239-253.
Turnhout, E., Dewulf, A. & Hulme, M. (2016). What does policy-relevant global environmental knowledge do? The cases of climate and biodiversity. *Current Opinion in Environmental Sustainability* 18: 65-72.
Turnhout, E., Gupta, A., Weatherley-Singh, J., Vijge, M., De Koning, J., Visseren-Hamakers, I. J., Herold, M. & Lederer, M. (2017). Envisioning REDD+ in a post-Paris era: Between evolving practice and current expectations. *WIREs Climate Change* 8:e425. doi: 10.1002/wcc.425
Turnhout, E., Hisschemöller, M. & Eijsackers, H. (2007). Ecological indicators: Between the two fires of science and policy. *Ecological Indicators* 7(2): 215-228.
Turnhout, E., Stuiver, M., Klostermann, J., Harms, B. & Leeuwis, C. (2013). New roles of science in society: Different repertoires of knowledge brokering. *Science and Public Policy* 40: 354-365.
Turnhout, E., van Bommel, S. & Aarts, N. (2010). How participation creates citizens: participatory governance as performative practice. *Ecology and Society* 15(4): 26.
UNEP/WMO (2011). *Integrated assessment of black carbon and tropospheric ozone*. Report, United Nations Environment Programme and World Metrorological Organization.
Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy* 28: 817-830.
Urpelainen, J. (2012). Geoengineering and global warming: a strategic perspective. *International Environmental Agreements: Politics, Law and Economics* 12: 375-389
Urry, J. (2014). The problem of energy. *Theory, Culture and Society* 31(5): 3-20.

Urry, J. (2016). *What is the Future?* Malden, MA: Polity Press.
Valvidia, M., Galan, J. L., Laffarga, J., & Ramos, J. L. (2016). Biofuels 2020: Biorefineries based on lignocellulosic materials. *Microbial Biotechnology* 9(5): 585-594.
van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D. & Cassen. C. (2020). Anticipating futures through models: Integrated Assessment Modeling in the climate science-policy interface since 1970. *Global Environmental Change* 65: 102191.
van der Duin, P. (2018). Toward 'responsible foresight': Developing futures that enable matching future technologies with societal demands. *World Futures Review* 11(1):69-79.
van der Linden. H. D. (2018). *NGO discourses on international governance for geoengineering.* Masters thesis. Utrecht University.
van der Sluijs, J. P. (2002). A way out of the credibility crisis of models used in intergrated environmental assessment. *Futures* 34: 133-146.
van Est, R. (2017). Responsible Innovation as a source of inspiration for Technology Assessment, and vice versa: the common challenge of responsibility, representation, issue identification, and orientation. *Journal of Responsible Innovation* 4(2): 268-277.
van Lente, H. (2000). Forceful Futures: From Promise to Requirement, in Brown, N, Rappert, B. & Webster, A. (Eds). *Contested Futures: A Sociology of Prospective Techno-science*. Aldershot: Ashgate, pp. 211-219.
van Oudheusden, M. (2014). Where are the politics in responsible innovation? European governance, technology assessments, and beyond. *Journal of Responsible Innovation* 1: 67-86
van Vuuren, D. P., Hof, A. F., van Sluisveld, M. A. E. & Riahi, K. (2017). Open discussion of negative emissions is urgently needed. *Nature Energy* 2: 902-904.
van Vuuren, D. P., Kok, M. T. J., Girod, B., Lucas, P. L. & de Vries, B. (2012). Scenarios in Global Environmental Assessments: Key characteristics and lessons for future use. *Global Environmental Change* 22: 884-895.
van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., . . . Winkler, H. (2013). A new scenario framework for Climate Change Research: scenario matrix architecture. *Climatic Change 122*(3): 373-386.
van Vuuren, D. P., Stehfest, E., den Elzen, M. G. J., Kram, T., van Vliet, J., Deetman, S., . . . van Ruijven, B. (2011). RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change 109*(1-2): 95-116.
Vervoort J. M. (2019). New frontiers in future games: Leveraging game sector development. *Futures* 105: 174-186.
Vervoort J. M., Bendor, R., Kelliher, A., Strik, O. & Helfgott, A. E. R. (2015). Scenarios and the art of worldmaking. *Futures* 74: 62-70.
Vervoort J. M. & Gupta A. (2018). Anticipating climate futures in a 1.5° C era: the link between foresight and governance. *Current Opinion in Environmental Sustainability* 31: 104-111
Victor, D. G. (2008). On the regulation of geoengineering. *Oxford Review of Economic Policy* 24(2): 322-336.
Victor, D. G., Morgan, M. G., Apt, J., Steinbruner, J., & Ricke, K. L. (2013) The truth about geoengineering: Science fiction and science fact. *Foreign Affairs* 92: 1-8
Victor, D. G., Zaelke, D., & Ramanathan, V. Soot and short-lived pollutants provide political opportunity. *Nature Climate Change* 5: 796-798.

Virgoe, J. (2009). International governance of a possible geoengineering intervention to combat climate change. *Climatic Change* 95: 103-119.
Waller, L., Rayner, T., Chilvers, J., Gough, C. A., Lorenzoni, I., Jordan, A., & Vaughan, N. (2020). Contested framings of greenhouse gas removal and its feasibility: Social and political dimensions. *WIREs Climate Change*, e649.
Wardropper, C. B., Gillon, S., Mase, A. S., McKinney, E. A., Carpentier, S. R. & Rissman, A. R. (2016). Local perspectives and global archetypes in scenario development. *Ecology and Society* 21(2): 12.
Waxman, A., R., Khomaini, A., Leibowicz, B. D., & Olmstead, S. M. (2020). Emissions in the stream: estaimating the greenhouse gas impacts of an oil and gas boom. *Environmental Research Letters* 15: 014004.
Weinberg, A. (1966). Can technology replace social engineering? *Bulletin of Atomic Scientists* 22(10): 4-8.
Wibeck, V., Hansson, A. & Anshelm. J. (2015). Questioning the technological fix to climate change – Lay sense-making of geoengineering in Sweden. Energy Research & Social Science 7: 23-30.
Wibeck, V., Hansson, A., Anshelm. J., Asayama, S., Dilling, L., Feetham, P. M., … & Sugiyama, M. (2017). Making sense of climate engineering: a focus group study of lay publics in four countries. *Climatic Change* 145(1-2): 1-14.
Wiertz, T. (2015). Visions of climate control: Solar radiation management in climate simulations. *Science, Technology & Human Values* 1-23. doi: 10.1177/0162243915606524
Wilcox, J., Psarras, P. C., & Liguori, S. (2017). Assessment of reasonable opportunities for direct air capture. *Environmental Research Letters* 12(6): 065001.
Wisner, B. (2020). Five years beyond Sendai – Can we get beyond frameworks? *International Journal of Disaster Risk Science* 11: 239-249.
Wyatt, S. & Balmer, B. (2007). Home on the range: Where is the middle in science and technology studies? *Science, Technology & Human Values* 32(6): 619-626.
Wynne, B., (1993). Public uptake of science: a case for institutional reflexivity. *Public Understanding of Science* 2: 321–337.

Samenvatting

Climate Imagineering: De politiek en praktijk van de evaluatie van zonlichtreflectie en koolstofverwijdering

Dit proefschrift onderzoekt recente voorstellen voor nieuwe koolstofputten (koolstofverwijdering, ‘carbon dioxide removal’, CDR) en zonlichtreflectie (‘solar radiation management’, SRM). Deze technieken worden vaak behandeld als vormen van ‘climate engineering’ (CE), gedefinieerd als opzettelijke en grootschalige klimaatinterventies. Ik onderzoek deze vormen van climate engineering als casestudy's van opkomende sociotechnische strategieën in klimaatbeheer. Ik onderzoek op toekomstverkenningen gebaseerd bewijs over SRM en CDR als resonante afbeeldingen van de toekomstige implementatie van deze technieken, en van de bijbehorende uitdagingen (wat bekend wordt), evenals reflecties van representatie (wie telt), procedure (hoe het wordt gedaan), epistemologie (hoe ze weten), en uitkomst (wat gebeurt er en wie profiteert).

Mijn specifieke onderzoeksgebied betreft de verborgen politiek van wetenschappelijke beoordeling: hoe kennis wordt geconstrueerd, aangevochten en gecommuniceerd door expertnetwerken, en hoe deze het begrip van toekomstige klimaatopties vormen. Ik baseer mijn vragen op verschillende aangrenzende literatuur-domeinen: analytische raamwerken van ‘Science and Technology Studies’ (paragraaf 1.4.1) en ‘governmentality studies’ (paragraaf 1.4.2) zoals ingezet in mondiale milieubestuurlijke kwesties. Ik onderzoek ook toekomstgerichte en stakeholdergerichte activiteiten - beschreven als gericht op anticipatie en deliberatie – gekaderd door frames voor technologiebeheer zoals Responsible Research and Innovation (RRI) (paragraaf 1.4.3).

De onderzoeksvragen die dit onderwerp ontleden zijn als volgt. Ten eerste: hoe wordt kennis en bewijs over SRM en CDR gecreëerd (hoofdstukken 2 en 3)? Ik richt me op wetenschappelijke expertnetwerken in het noorden van de wereld en de doelstellingen, epistemologieën en effecten van hun toekomstverkennende praktijken. Ten tweede: wat doet deze kennis (hoofdstukken 2, 3, 4 en 5)? Ik onderzoek hoe toekomstverkennende praktijken resonante termen en referentiekaders inzetten die actief - zij het onvolkomen - klimaatbeheer naar hun eigen ingezette beelden vormen. Ten derde: hoe kan deze kennis worden gebruikt om verschillen te overbruggen (hoofdstukken 5 en 6)? Ik ga van het begrijpen van de geconstrueerdheid van kennis naar het focussen op die constructie als een vorm van experimentatie, waarbij ik me bezighoud met expertnetwerken en kennistypen om toekomstverkennende praktijken te gebruiken als platforms die richtingen voor onderzoek en beleid verkennen.

De hoofdstukken vertegenwoordigen drie richtingen. De eerste is van analytisch naar toegepast werk, waarbij gebruik wordt gemaakt van kritische verbeeldingen van de kenniseconomie om overbruggingsactiviteiten tussen experts en belanghebbenden te contextualiseren en te informeren. De tweede is van retrospectief tot generatief werk - van analyse van hoe kennis wordt geconstrueerd naar activiteiten die de toekomst gebruiken als een experimentatieruimte of zandbak om nieuwe kennis te genereren, die op hun beurt SRM- en CDR-beoordelingen vorm geven. De uiteindelijke richting beweegt van algemene technologische categorieën naar specifieke benaderingen,

waarbij ik me eerst richt op de bredere politiek van planetaire interventies, en vervolgens op de politiek van specifieke benaderingen en de bijbehorende expertnetwerken.

Ik begin met een paar interpretatieve reviews. *Tools of the Trade* (hoofdstuk 2) plaatst een 'deductieve' (elders in het proefschrift noem ik dit missie-georiënteerd) assessment-methode -waarbij voorrang wordt gegeven aan bruikbaar bewijs voor beleidspubliek- tegenover een 'deliberatieve' modus die gericht is op een open beoordeling met diverse belanghebbenden. *The Practice of Responsible Research and Innovation* (Hoofdstuk 3) biedt een meer kritisch perspectief op deliberatieve activiteiten en wijst erop dat deze activiteiten, door zichzelf te contrasteren tegen meer missiegericht werk, zich toch bezighouden met dezelfde impliciete en instrumentele politiek van bewijsvoering. *Delaying Decarbonization* (hoofdstuk 4) onderzoekt het langere en bredere narratief van klimaatbeheer, waarbij SRM en CDR worden behandeld als sociotechnische strategieën die putten uit dezelfde politieke beweegredenen die een groot aantal antecedente strategieën hebben geïnformeerd, van marktmechanismen en CCS tot schaliegas en klimaatverontreinigende stoffen met een kort bestaan.

Ik sluit af met een paar overbruggende en generatieve beschouwingen over bepaalde benaderingen. *Is Bioenergy Carbon Capture and Storage Feasible?* (Hoofdstuk 5) betrekt leden van IAM-onderzoeksgroepen en een multidisciplinaire groep van kritische experts, en conludeert dat perspectieven op hoe de 'haalbaarheid' van nieuwe klimaatopties moet worden berekend een reflectie is van perspectieven op de huidige en toekomstige rol van IAM-werk in klimaatbeleid. *Engineering Imaginaries* (Hoofdstuk 6) betrekt wetenschappers die betrokkken zijn bij vroege gesprekken over de risicoprofielen en het juiste beheer van een specifiek planetaire vorm van SRM, en onderzoekt de waarde van toekomstverkennende benaderingen om tot wederzijds leren komen tussen diepgewortelde perspectieven, die op hun beurt robuust zijn tegen een breed scala aan toekomstige plausibiliteiten.

Curriculum Vitae

Professional Experience

Academic Positions

2021– Post-doctoral Researcher – Aarhus University, Denmark

2012–2021 Research Associate – Institute for Advanced Sustainability Studies, Germany

2018 Visiting scholar – School for the Future of Innovation in Society, Arizona State University, USA

2010–2012 Research Associate - Centre for International Governance Innovation, Canada

Science Management

2015–2016 Project Lead – Solar Radiation Management: Foresight for Governance (SRM4G) – multi-workshop scenario-based stakeholder engagement

2012–2015 Lead Editor and Manager – Working Paper series 'Geoengineering Our Climate?'

Education

Formal

2019–2021 Doctor of Philosophy - Copernicus Institute of Sustainable Development, Utrecht University

2009–2010 Master of Arts in Global Governance - University of Waterloo

2001–2005 Bachelor of Arts in Political Science (Honours) - University of British Columbia

Short Course Training

2017 European Consortium for Political Research Summer School – Qualitative Data Analysis

2016 CNS-Arizona State University Winter School - Anticipatory Governance of Emerging Technologies

Grants and Awards

2009 Bombardier CGS Masters Scholarship, Social Science & Humanities Research Council of Canada

2009 Balsillie Student Fellowship & President's Scholarship, University of Waterloo

Publications

Peer-reviewed

2020 **Low, S.** and Boettcher, M. Delaying Decarbonization: Climate governmentalities and sociotechnical strategies from Copenhagen to Paris. *Earth System Governance.* DOI: 10.1016/j.esg.2020.100073

2020 **Low, S.** and Honegger, M. A Precautionary Assessment of Systemic Projections and Promises in Sunlight Reflection and Carbon Removal Modeling. *Risk Analysis.* DOI: 10.1111/risa.13565

2020 Morrow, D. R., Thompson, M. S., Anderson, A., Batres, M., Buck, H. J., Dooley, K., Geden, O., Ghosh, A., **Low, S.**, Njamnshi, A., Noel, J., Olufemi, O. T., Talati, S., and Wilcox, J. Principles for Thinking about Carbon Dioxide Removal in Just Climate Policy. *One Earth*. DOI: 10.1016/j.oneear.2020.07.015

2020 **Low, S.** and Buck, H.J. The Practice of Responsible Research and Innovation in 'Climate Engineering'. *WIREs Climate Change* 644. DOI: 10.1002/wcc.644

2020 **Low, S.** and Schäfer, S. Is Bio-energy CCS Feasible? The contested authority of integrated assessment modeling. *Energy Research & Social Science* 20, 101326.

2019 **Low, S.** and Schäfer, S. Tools of the Trade: Practices and politics of researching the future in climate engineering. *Sustainability Science*, DOI: 10.1007/s11625-019-00692-x

2017 **Low, S.** The Futures of Climate Engineering. *Earth's Future*, 5(1): 67-71.

2017 **Low, S.** Engineering Imaginaries: Anticipatory Foresight for Solar Radiation Management Governance. *Science of the Total Environment*, 580: 90-104.

2014 Schäfer, S. and **Low, S**. Asilomar Moments: Formative Framings in Recombinant DNA and Solar Climate Engineering Research. *Philosophical Transactions of the Royal Society A*, 372(2031).

2013 Schäfer, S., Irvine, P.J, Huber, A.M., Reichwein, D., **Low, S**., Maas, A., and Lawrence, M.G. Field Tests of Solar Climate Engineering. *Nature Climate Change*, 3(9): 766.

Edited Volumes

2018 Blackstock, J.J. and **Low, S.** (eds). *Geoengineering Our Climate? Ethics, Politics and Governance.* London: Earthscan-Routledge.

Chapters

2018 Gabriel, J. and **Low, S**. "Foresight in Climate Engineering." In Blackstock, J.J. and **Low, S.** (eds). *Geoengineering Our Climate? Ethics, Politics and Governance.* London: Earthscan-Routledge.

2018 Schäfer, S. and **Low, S**. "The Discursive Politics of Expertise: What Matters for Geoengineering Research and Governance." In Trentmann, F., Sum, A.B. and Rivera, M. (eds), *Work in Progress: Economy and Environment in the Hands of Experts.* Munich: Oekom.

2013 **Low, S.**, Moore, N., Chen, Z., McManamen, K. and Blackstock, J.J. "Geoengineering Policy and Governance Issues." In Lenton, T. and Vaughan, N. (eds), *Geoengineering Responses to Climate Change.* New York: Springer.

2011 Milkoreit, M., **Low, S.**, Vargas Escarraman, R. and Blackstock, J.J. "The Global Governance of Geoengineering: Using red teaming to explore future agendas, coalitions and international institutions." CEADS Papers Volume 1: Red Teaming, 56

Reports and Assessments

2016 Boettcher, M., Gabriel, J. and **Low, S.** *Solar Radiation Management: Foresight for Governance*. Institute for Advanced Sustainability Studies.

2015 Schäfer, S., Lawrence, M.G., Stelzer, H., Born, W. and **Low, S.** (eds). *The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth*. Funded by the European Union's Seventh Framework Programme under Grant Agreement 306993.

2013 Banerjee, B, Collins, G., **Low, S.**, and Blackstock, J.J. *Scenario Planning for Solar Radiation Management.* Yale Climate and Energy Center.

Presentations

2020 *A Precautionary Assessment of Systemic Projections in SRM and CDR modeling.* Society for Risk Analysis, Austin, USA.

2020 *Delaying Decarbonization from Copenhagen to Paris.* 4S/EASST, Prague, Czech Republic.

2019 *Climate Engineering and Future Natures*. Workshop, Potsdam, Germany.

2019 *Understandings of Feasibility and Agency in Integrated Assessment Modeling*. Imagined Societies and Policymakers Workshop, Hamburg, Germany.

2019 *The Feasibility of Bioenergy CCS*. Ethics and Values in Assessment, Mercator Institute, Berlin, Germany.

2019 *Does Climate Engineering pose Systemic Risks?* Society for Risk Analysis, Potsdam, Germany.

2019 *The Feasibility of Negative Emissions: Perspectives on modeling for climate policy.* Scenarios Forum, Denver, USA.

2018 *Perspectives of integrated assessment modelers and their critics on bioenergy CCS.* EASST, Lancaster, UK.

2017 *Claiming and Making the Future in Solar Geoengineering: A focus on methods.* 4S, Boston, USA.

2017 *Letting the Numbers Speak: Engaging integrated assessment modelers and their critics on bioenergy CCS.* Anticipation, London, UK.

2016 *Engineering Imaginaries: Anticipatory foresight for climate engineering governance.* S.Net, Bergen, Norway.

2016 *Scenarios, Imaginaries, and Solar Geoengineering Governance.* EASST, Barcelona, Spain.

2016 *Flash Scenarios: Climate engineering futures.* Academic Working Group meeting, Forum for Climate Engineering Assessment, NY, USA.

2015 *Solar Radiation Management: Foresight for Governance. A Case Study in Anticipatory Foresight.* Anticipation 2015, Trento, Italy.

2014 *Asilomar Moments: Implications for Governance of Formative Framings in Recombinant DNA and Solar Climate Engineering Research.* Self-governance in Science and Technology Workshop, Potsdam, Germany.

2013 *Technical Thresholds and Societal Concerns: Competing Framings and Implications for Governance.* Workshop, University College London, UK.

2013 *Comparing Early Risk Perceptions of Biotechnology and Climate Engineering: Repercussions for Governance.* ECPR Joint Sessions Workshop, Mainz, Germany.

Events organized

2021 **Steering Committee** - *Climate Engineering Conference 2021*. Fall, Berlin.

2017 **Session Lead Organizer** – *Modeling, imagining, and making the future.* Climate Engineering Conference 2017: Berlin.

2017 **Steering Committee** - *Climate Engineering Conference 2017*. Oct 9-12, Berlin.

2016 **Session Co-organizer** - *Flexing and Reflexing Authority in STS Engagements.* Nov 12, Workshop at S.net Conference, Bergen

2015 **Workshops Lead Organizer** - *Solar Radiation Management: Foresight for Governance*. Jul 13–14; Aug 27–28; Nov 12–13, Series of three workshops at Institute for Advanced Sustainability Studies.

2014 **Steering Committee** - *Climate Engineering Conference 2014.* Aug 18-21, Berlin.

2014 **Session Lead Organizer** - *Climate Engineering in Popular Culture: Art, Media, Games and Fiction.* Climate Engineering Conference 2014: Berlin.

2014 **Session Co-organizer** - *Linkages between Climate Engineering and Short-lived Climate Forcing Pollutants.* Climate Engineering Conference 2014: Berlin.

2014 **Session Co-organizer** - *Self Governance in Science and Technology*. Apr 14-15, Workshop at Institute for Advanced Sustainability Studies.

2012 **Conference Co-organizer** - *Geoengineering Our Climate? Ethics, Politics and Governance.* Jan 18-20, Conference, Ottawa.

Acknowledgements

In the finest Canadian tradition, I apologize to everyone who warned me against undertaking a PhD, as well as to everyone who encouraged me to do so.

First and foremost, I would like to thank Prof. Frank Biermann and Dr. Joost Vervoort for their keen insights and good humour, for their hospitality during time spent at the Copernicus Institute of Sustainable Development at Utrecht University, and for their tireless enthusiasm and guidance in the great and small matters of research. I will work here someday, and that is a promise. Thanks are due also to Prof. Mark Lawrence for giving me and so many close friends a chance to work together at the Institute for Advanced Sustainability Studies – which also provided the resources that made this thesis and its constituent projects possible. Although many years have since passed, my thanks to Dr. Jason Blackstock, who introduced me to the topic of 'geoengineering' in 2010 – and kicked off a sequence of events in my life that are still unfolding. And for a few short weeks at Arizona State University, Cynthia Selin and colleagues showed me the dynamism of the School for the Future of Innovation in Society. For shelter and support, thank you all!

I would also like to thank the wider 'geoengineering' community – even if half the people in it would dispute its existence. Thanks for being great colleagues, better friends, and from time to time, my data points. Nigel Moore and George Collins set the bar as fine minds, but finer souls. Professors Holly Buck, Clare Heyward, Pete Irvine, Ben Kravitz, and Duncan McLaren, my hearty congratulations to you all. A salute to Pablo Suarez, a force for good in this crazy world, and to everyone named 'Oliver'. My appreciation (and apologies) to all the members of the Climate Engineering Conference Steering Committees, and numerous versions of the Climate Engineering and Systemic Risk groups at the IASS, for rounding the sharp edges on my points of view. Thank you to everyone who co-authored and reviewed an article I published, participated in a meeting I helped organized, or bought me a drink in Barcelona, Bergen, Berlin, Boston, Denver, Hamburg, Lancaster, London, New York, Phoenix, Potsdam, and Trento.

Deepest respects to Steve Rayner, Jón Egill Kristjánsson, and Paul Crutzen – I did not know them as well as I would have liked, but they mattered to those who matter to me, and they cast a long light.

Shana, Vanessa, and family – thanks for your support, even though I'm not that kind of doctor! Nick, Garreth, Brie, Mike, and all the others I came up through the ranks with at the University of British Columbia; Marcos, Mel, Milad, Matt, Andrew, Conrad, Graham and all the others at the University of Wateroo – I have not forgotten where it all began. My thanks to the Woolly Gang for many a pleasant afternoon – it was inside us all along. The 'MacGuffin' device that ushers in my thesis comes from time well wasted with Skeleton Brains, our wondrously piratical improv theatre troupe – where I learned that the more you share, the more you have. My gratitude to all the Berliners, old and new, who shared their time with me, and made the city a place to grow young.

Kieran and Gavin – the days pass like years, and the years like days. Tim Butler and Andy Parker – We've come a long, long way together; I have to praise you like I should.

Matthias Honegger, you have been a packhorse, a path-finder, and an unshakable moral compass.

Miranda – If I had only met you today, I would do it all again.