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Governing geoengineering sustainably: a scenario exercise to inform Australian geoengineering policy development

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Governing geoengineering sustainably:

A scenario exercise to inform Australian geoengineering policy development

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Abstract

Geoengineering, the *technofix* to climate change, is a complex, contentious and high-stakes proposal. Yet in the absence of credible long-term global emissions reduction, the idea cannot be overlooked. To ensure that geoengineering contributes to sustainable environmental and social outcomes, a forward-looking, inclusive and reflexive decision-making framework is needed. Instead, Australia's history on climate policy reflects a short-sighted, impulsive and polarised approach. The motivation of this project is therefore to inform sustainable geoengineering governance in Australia. Within a sustainable governance context, scenarios are often used in the management of long-term, complex, and uncertain issues. This thesis investigates how a scenario exercise can inform sustainable geoengineering governance in Australia.

The sustainability focus justifies an interdisciplinary mixed-methods approach. The thesis begins by surveying the present before interrogating the future and is presented as a compilation of five papers. First, the thesis explores from an Earth System Governance perspective what global geoengineering governance exists and how this might evolve. The analysis characterises geoengineering governance as *governance-by-default* where there is no purposive regulation—decisions are guided by existing norms and driven by the motivations of engaged academics. Given the influence of these actors, the research examines, through a systematic quantitative review, the types of geoengineering governance frameworks proposed in academic and non-academic literature. The study finds that the challenges of geoengineering governance can be likened to issues in other policy domains but suggests that normalising the debate thusly could obscure major threats and novel opportunities.

Next, a meta-analysis of geoengineering scenarios is undertaken. It finds that the treatment of geoengineering within these scenarios does not align with sustainability concepts. An emphasis on technological solutions ignores the interdependence of nature and society and conceals alternative options; a focus on global effects and actions disregards local or regional issues; and scenarios portray only a narrow range of perspectives.

Finally, an inductive and deductive scenario design method is proposed and demonstrated, producing four scenarios that are analysed in several ways: their key determinants are compared to those of scenarios in the geoengineering literature; they are studied individually and collectively to identify causal relationships and early warning signals; shared learning throughout scenario process is explored; and finally, they are used to stress-test climate policies and inform robust strategies.

Proposed Australian climate strategies are found not to be robust. Policies are based on the expectation of enduring government legitimacy and that technological solutions obviate the need for behavioural change. The geoengineering strategy proposed for Australia is engagement nationally and internationally on geoengineering issues in a technologically and ideologically neutral manner and investment in transparent and inclusive research.

The contributions of this thesis are several. It establishes that geoengineering governance is not tracking on a sustainable trajectory globally. It suggests that the role of scenarios, already central to geoengineering scholarship and governance design, can be expanded. It proposes and demonstrates a successful scenario development and analysis method. It begins a cross-sectoral Australian geoengineering conversation. It makes specific policy recommendations; and in doing so, it opens up the scope of policy options.

Declaration by the author

The thesis comprises my original work towards the degree of Doctor of Philosophy. Where others have contributed, for example in jointly-authored papers, their contribution has been clearly indicated. Due reference has been made everywhere in the text where non-original material has been used. The thesis is fewer than 100,000 words, exclusive of tables, maps, bibliographies and appendices.

Anita Talberg

Publications during candidature

Peer reviewed papers

Talberg, A., Thomas, S., & Wiseman, J. (2018). A scenario process to inform Australian geoengineering policy. *Futures*, *101*, 67–79. https://doi.org/10.1016/j.futures.2018.06.003

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There are similarities between a PhD and a first pregnancy. In both cases you go into the experience not quite knowing what to expect but comforted by the knowledge that others done it before you (so it must be manageable—right?). Each stage is unlike anything that you have experienced and just as you get used to it, it inevitably changes. Everyone is full of advice, none of which seems to help in your personal situation. Your supervisors, much like an obstetrician, are there to make sure that you do not actually die and that all vital signs are within the very broad parameters of normality, but beyond that they cannot help you carry the load. You are alone on this one. Your partner can be as supportive as humanly possible and empathise with you day and night, but in reality, they have only a vague understanding of what you are going through and can offer only words of encouragement.

It is often said that the strains of pregnancy and the pains of labour quickly fade from memory, otherwise humans would become extinct. I imagine, too, that the sufferings of the PhD process are soon forgotten as we move into new careers. However, there are a number of people whom I got to know through the experience that I will never forget. There are things that were done for me and said to me that were so meaningful and motivating that they have become part of who I now am. I would like to pay tribute to those people.

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List of abbreviations

ATS	Antarctic Treaty System
BECCS	Bioenergy with carbon capture and storage
CBD	Convention on Biological Diversity
CCA	Climate Change Authority
CCS	Carbon capture and storage
CCT	Cirrus cloud thinning
CDR	Carbon dioxide removal
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CO2	Carbon dioxide
COP	Conference of the parties
DAC	Direct air capture
ENMOD	Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques
ENTRI	Environmental Treaties and Resources Indicators
ERF	Emissions Reduction Fund
ESG	Earth System Governance
GeoMIP	Geoengineering Model Intercomparison Project
IGO	Intergovernmental organisation
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
KSF	Key success factors
LC	London Convention
LP	London Protocol
MCB	Marine cloud brightening

MARPOL	International Convention for the Prevention of Pollution from Ships
NCESS	National Committee for Earth System Science
NGO	Non-governmental organisation
OSTs	Outer Space Treaties
OODA	Observation, orientation, decision, action
RCPs	Representative Concentration Pathways
SAI	Stratospheric aerosol injection
SBSTTA	Subsidiary Body on Scientific, Technical and Technological Advice
SPICE	Stratospheric Particle Injection Climate Engineering
SRES	Special Report on Emissions Scenarios
SRM	Solar radiation management
SRMGI	Solar Radiation Management Governance Initiative
SWOT	Strengths, weaknesses, opportunities, threats
TCFD	Task Force on Climate-related Financial Disclosures
TOWS	Threats, opportunities, weaknesses, strengths
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNCLOS	United Nations Convention on the Law of the Sea
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNTC	United Nations Treaty collection

Chapter 1 - Introduction

1.1 Context

Climate policy is the Achilles heel of Australian governments. Divided and often polarised views on climate policies run deep both between and within political parties (Talberg et al., 2013). Since 2009, climate policies have led to the premature and dramatic ousting of three Australian Prime Ministers and one Opposition Leader. The likelihood of an enduring and effective climate strategy in Australia is increasingly narrow (Talberg, 2016) and Australia's greenhouse gas emissions have increased year-on-year since 2014 (Department of the Environment and Energy, 2018).

To meet politically agreed limits to global warming (Schleussner et al., 2016b), lasting national climate policies are needed that provide 'challengingly deep and rapid mitigation' (Millar et al., 2017, p. 741), but the sum of current and proposed national efforts falls well short of this (Sanderson et al., 2016). Global greenhouse gas emissions continue to increase, and as they do, so does interest in alternative climate policy responses: removing existing atmospheric greenhouse gases or adjusting levels of solar radiation. These responses are collectively known as geoengineering, climate engineering, climate intervention, or climate modification.

In international climate negotiations, geoengineering began as a topic of both scientific curiosity and political controversy. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) published in 2013-14 was the first to include entire sections dedicated explicitly to geoengineering matters (Boucher et al., 2013; Ciais et al., 2013). However, geoengineering was also included *implicitly* within the modelling and assumptions underlying the science of the report. The majority of emissions pathways to 2100 considered in the report as consistent with limiting warming to 2°C assumed some form of geoengineering in the second half of the century (Fuss et al., 2014). Some have noted that geoengineering has become 'by stealth' (Parker and Geden, 2016) the accepted concession for avoiding dangerous climate change.

In Australia, the emergence of geoengineering ideas has occurred in an equally opaque and inelegant manner. The Australian government has engaged inconsistently on geoengineering matters nationally and internationally, sometimes actively driving reform (LC/LP, 2009) or funding research (Frydenberg, 2018), and at other times failing to raise the issue. In the background, parts of Australian civil society have proposed a broad range of geoengineering projects to be included as part of a domestic climate strategy (Pinder, 2014; Spratt, 2016). Yet to date, the Australian government has proposed no geoengineering agenda, and no government organisation has described an official planned intention to explore (or not) geoengineering options as part of a broader mandate.

This thesis is thus set in the context of geoengineering appearing 'by stealth' in international climate policy decision-making, while Australia adopts a seemingly haphazard approach to geoengineering policy and funding. Australia's approach is not based on any form of public dialogue or consultation and exists against the background of consecutive governments repeatedly failing to establish a consistent and lasting climate strategy over the past decade.

1.2 Problem statement

Whether Australia's uncalculated approach to geoengineering is problematic depends on the stakes of geoengineering. These differ widely by technology and their envisaged use. Some of the more serious adverse effects of geoengineering suggested by research are connected to methods for adjusting levels of solar radiation. Robock (2016) lists 27 risks or concerns associated with this type of geoengineering, ranging from environmental risks, such as disrupting weather systems so as to affect drought conditions in Africa and Asia, or slowing the recovery of the ozone layer, to ethical concerns, such as potential weaponisation. It is important to note, however, that these risks depend heavily on how the technology is used; for example, rapid deployment and termination is likely to have more severe impacts on biodiversity through local extinctions than a slowly-ramped up deployment (Trisos et al., 2018), whereas a more moderate use could avoid such problems (Keith and MacMartin, 2015; Sugiyama et al., 2017a). A crucial point from Robock's list is that just seven of the 27 risks relate to physical and biological systems. The other 20 relate to potential effects on society. Here too the stakes could be high. For example, risk number 23 refers to the potential for interstate conflict and risks to national security. Number 25 is the risk that geoengineering supresses governments' incentive to reduce emissions, thereby creating increased reliance on geoengineering methods.

These risks must be considered in the context of the proposed benefits of geoengineering against a counterfactual of potentially unmitigated climate change. The majority of global climate models anticipate that the global average temperature will exceed 2°C above preindustrial levels by 2100, except under the strongest mitigation scenarios proposed (and those scenarios generally assume some form of negative emissions) (Collins et al., 2013). Warming of 2°C above preindustrial levels is associated with regionally relevant increases in the frequency and/or intensity of extreme heat, flood and drought events, disrupted and often reduced agricultural and fisheries productivity, and loss of terrestrial and marine biodiversity (O'Neill et al., 2017; Schleussner et al., 2016a). In Australia, 2°C of warming could as much as double the likelihood of already witnessed extreme climate events, such as the 'Angry summer' of 2012-13, or the coral bleaching event of 2016 (King et al., 2017).

The stakes of geoengineering are therefore high. Effective deployment might substantially reduce impacts on human health and livelihoods while decelerating biodiversity loss. Unsuccessful deployment, especially against the backdrop of increasing greenhouse gas emissions, could exacerbate climate impacts or even result in a raft of new adverse social and environmental outcomes. Merely defining what might be considered successful or unsuccessful deployment is value-laden. Geoengineering is characterised as a 'wicked problem' (Abelkop and Carlson, 2012): it is difficult to define, complex, dynamic, unbounded, and presents unique challenges when viewed at different temporal and spatial scales or through different normative lenses (Funtowicz and Ravetz, 1994; Rittel and Webber, 1973).

1.3 Aim and scope

The thesis rests on the premise that the high stakes of geoengineering combined with Australia's disappointing history on climate policies suggest that investigation into, or engagement with, geoengineering should be guided by a cautious, long-term and bipartisan strategy. Successfully designing such a strategy entails managing high levels of scientific uncertainty and complexity, disputed values and urgency in relation to both climate change and geoengineering (Funtowicz and Ravetz, 1994). It also requires forward-thinking. Participatory and exploratory scenarios are fundamental tools of forward-thinking and can help in navigating the 'wickedness' of geoengineering (Wilkinson et al., 2013). Australian governments, particularly at the subnational level, have some knowledge and experience in using scenarios in the climate policy space, but this is not widespread and is primarily focussed on climate adaptation decision-making (Rickards et al., 2014a; 2014b). The aim of this thesis is therefore to progress understanding on whether and how scenarios might be used to inform sustainable geoengineering policy in Australia.

The main research question of this thesis is therefore: **how can a scenario exercise inform sustainable geoengineering governance in Australia?** However, as noted by Einhorn and Hogarth (1982) in the very first issue of the *Journal of Forecasting*, making sense of the future 'depends to a considerable degree on making sense of the past' (1982, p. 24). Thus, several steps are needed before the main research question can be addressed.

The research first describes and critically analyses the broader context of geoengineering governance. After some background provided in Chapter 2, the research begins with Chapter 3 exploring the current state of global geoengineering governance. The findings from this analysis suggest that engaged researchers and scholars are key actors in the development of geoengineering governance mechanisms with significant influence over the trajectory of geoengineering. Therefore, in Chapters 4 and 5, the research explores the expectations and assumptions of these actors. Specifically, Chapter 4 is a review of governance designs proposed by these crucial actors, and Chapter 5 is a meta-analysis of these actors' uses of scenarios. This helps to strengthen understanding of the ways in which these actors envisage the future of geoengineering, because scenarios, as interactive and social tools of applied research, cannot be seen as separate to the context of analysis—they can change the course of events (Einhorn and Hogarth, 1982).

Building on the findings from these three chapters, Chapters 6 and 7 address the central thesis question. Chapter 6 demonstrates a method of scenario construction resulting in four multi-scale scenarios. These are analysed in two different ways in Chapters 6 and 7 to determine whether scenarios can inform sustainable geoengineering policy. Chapter 6 gleans insight directly from the scenario content, whereas Chapter 7 uses the scenarios to stress-test policy proposals.

The specific research questions addressed in this thesis are:

RQ#1: Is global geoengineering governance currently on a trajectory towards sustainable outcomes?

(1) What existing governance instruments are relevant to geoengineering?

(2) Who are the principal actors currently engaged in geoengineering?

(3) What are the features and likely outcomes of geoengineering governance?

RQ#2: Are proposed geoengineering governance designs in line with a sustainability agenda?

RQ#3: How do academics envision geoengineering?

(1) How are scenarios used in geoengineering research?

(2) What are the key characteristics of geoengineering scenarios?

(3) What assumptions and expectations do they suggest?

(4) What are the sustainability science implications?

RQ#4: How can a scenario exercise inform sustainable geoengineering governance in Australia?

1.4 Significance

The thesis has several intended outcomes. It aims to advance knowledge on geoengineering governance by taking stock of what is already occurring and what is being proposed, and then proposing an anticipatory approach to designing governance. In focussing on Australia, it starts to fill a gap in the literature that exists around geoengineering perspectives in both the Southern Hemisphere and the Asia Pacific. It aims to highlight the lack of open debate in Australia on geoengineering issues and on a practical level it starts that conversation through a scenario process that is meticulously documented. In doing so, it also aims to demonstrate a technique and format for Australian academics, in tandem with policymakers, to address emerging 'wicked' issues.

1.5 Methodological approach

'Wicked problems' and problems of sustainability are by definition unbounded and cannot be addressed within disciplinary boundaries (Funtowicz and Ravetz, 1994; Komiyama, 2011; Rittel and Webber, 1973). The research objective of the thesis and the research questions must therefore also draw on interdisciplinary perspectives and mixed methods (Lang et al., 2012; Sugiyama et al., 2016). At a high level, the research is founded on the epistemological concept of constructionism and pragmatist theoretical perspectives (Bryant and Charmaz, 2007). The pragmatist perspective draws on both empirical and rational/deductive knowledge methods for understanding a problem so as to deliver practical outcomes (Moon and Blackman, 2014). In each instance, the specific research question determined the selection of methods. As a result, the thesis comprises a mix of methodological approaches, each of which is detailed and justified within the chapters and summarised in Table 1.1.

Table 1.1: Methodologies employed in each chapter of the thesis

Chapter	Research questions	Methods	References
Chapter 3	Is global geoengineering governance currently on a trajectory towards sustainable outcomes? (1) What existing governance instruments are relevant to geoengineering? (2) Who are the principal actors currently engaged in geoengineering? (3) What are the features and likely outcomes of geoengineering governance?	Data collection, review and document analysis	Biermann et al., 2010 Finnemore and Sikkink ,1998
Chapter 4	Are proposed geoengineering governance designs in line with a sustainability agenda?	Systematic quantitative literature review and inductive thematic analysis	Boyatzis, 1998 Pickering and Byrne, 2014

Chapter 5	How do academics envision geoengineering? (1) How are scenarios used in geoengineering research? (2) What are the key characteristics of geoengineering scenarios? (3) What assumptions and expectations do they suggest? (4) What are the sustainability science implications?	A combination of systematic literature review and meta-analysis using quantitative and qualitative methods	Cooper et al., 2009 Pickering and Byrne, 2014
Chapter 6	How can a scenario exercise inform sustainable geoengineering governance in Australia?	Inductive and deductive scenario construction method derived from the Mānoa School Scenario Modeling Method	Dator, 2009 Schwartz, 1991
Chapter 7	How can a scenario exercise inform sustainable geoengineering governance in Australia?	Scenario and policy analysis	Obrien and Meadows, 2013 Wilson, 2000

The method followed in Chapter 3 is qualitative, normative document analysis on relevant international treaties identified from two databases and on related academic and non-academic literature. The analytical method draws elements from the Earth System Governance (ESG) framework (Biermann et al., 2010), specifically concepts of architecture, agency and norms. Norms are further defined with reference to Finnemore and Sikkink (1998).

Chapter 4 applies a systematic, quantitative review method (Pickering and Byrne, 2014) and relies on inductive thematic analysis (Boyatzis, 1998). The data consists of geoengineering governance proposals literature drawn from academic and non-academic databases.

A similar method is followed in Chapter 5, where the geoengineering scenarios literature is interrogated. However, in Chapter 5, the analytical method, which is both quantitative and qualitative, is more accurately described as a meta-analysis focussing primarily on the scenarios, their construction method/s and any justifications for these proposed by the authors (Cooper et al., 2009).

In Chapter 6 an inductive and deductive scenario design method is proposed based on the Mānoa School Scenario Modeling Method (Dator, 2009) and elements of the intuitive logics scenario method (Schwartz, 1991). Finally, Chapter 7 uses the scenarios created in Chapter 6 and proposes a scenario analysis method based on principles described by Wilson (2000), O'Brien and Meadows (2013), and others.

1.6 Thesis structure

The research is incremental and sequential, in that findings from each stage inform the design of the next. It begins by investigating from an ESG perspective what geoengineering governance exists at a global level and how this might develop into the future (Chapter 3), as a way to understand Australia's place in the global context. The next stage is to understand, given the 'institutional void' (Hajer, 2003) within which geoengineering sits, what types of governance mechanisms are proposed at a global level (Chapter 4). Given the important role of scenarios in geoengineering research, the next stage seeks to increase knowledge of how geoengineering scenarios have been used to date and the relevance of this for sustainable governance (Chapter 5). Finally, a scenario workshop was run to start a conversation on geoengineering in Australia as a way to investigate how scenarios can be used to inform Australian governance of geoengineering (Chapters 6 and 7).

The thesis consists of eight chapters (Figure 1.1) of which five are either papers published during the course of the candidature or manuscripts currently under peer-review. The findings from each chapter inform the design of research in subsequent chapters.

Chapter 1 introduces the context, the problem and the research questions. Chapter 2 provides the background and literature of relevance to the study. Chapters 3, 5 and 6 are published journal articles. Chapters 4 and 7 are manuscripts currently under peer-review. The danger of presenting a thesis by publication is that the thread of the research can be lost. Therefore, to ensure a well-integrated thesis that is easy to follow, before each of the five central chapters, a short section describes the place of the chapter in the thesis, and following each chapter, a short section describes the contribution of the chapter to the thesis. Chapter 8 then concludes by synthesising the main findings, the challenges and limitations of the research, and the major contributions and by providing directions for future research.

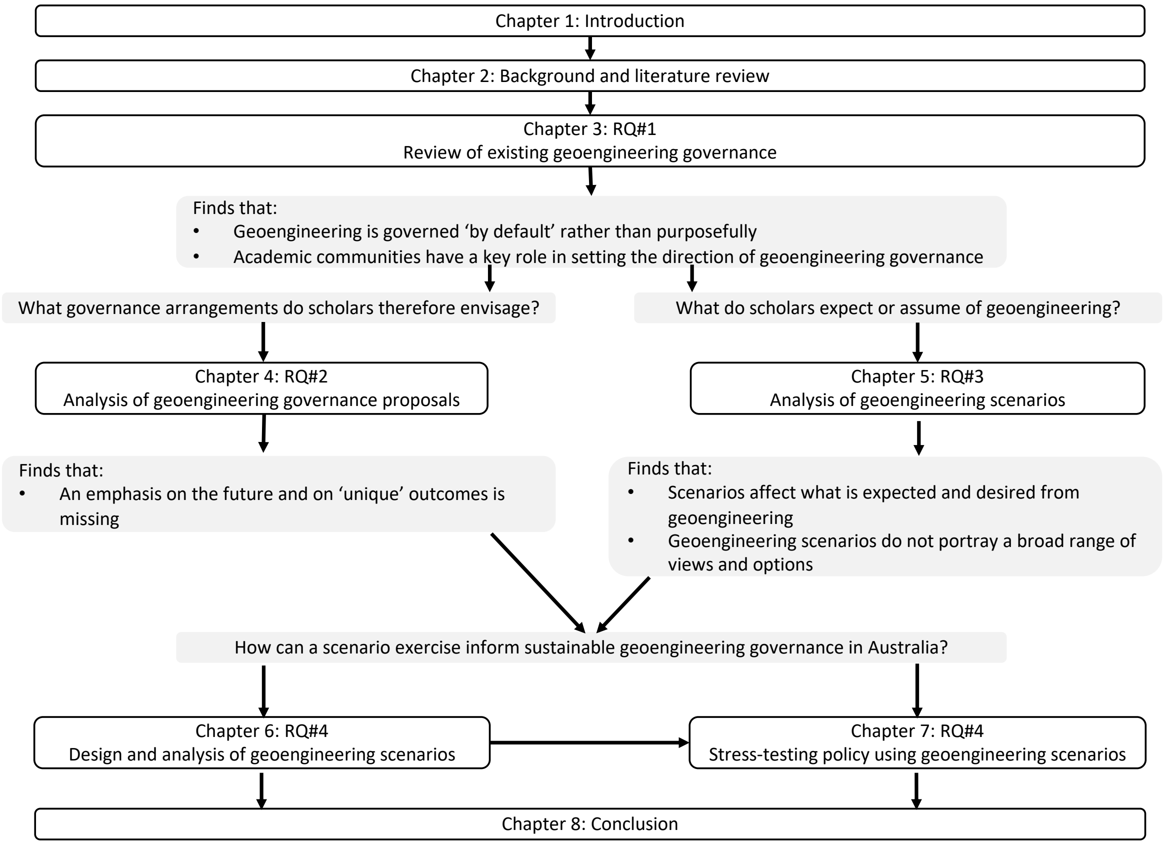

Figure 1.1: The structure of the thesis illustrating the incremental and sequential nature of the research

Chapter 2 – Literature and background

2.1 The emerging field of geoengineering

No undisputed definition for geoengineering exists, but a commonly quoted one is that of the Royal Society, which defines geoengineering as ‘deliberate large-scale intervention in the Earth’s climate system, in order to moderate global warming’ (Royal Society, 2009, p. ix). This subsection provides a brief and early history of geoengineering, and overviews of the main technologies proposed and scholarship to date.

2.1.1 A brief geoengineering history

It is difficult to point to an unequivocal beginning to geoengineering research. Initial mentions of climate control ideas, which can be traced back to the late-1800s, are tightly linked to proposals for weather modification, such as rainmaking (see for example Powers, 1890) and to early scholarship on the science of climate change (see for example Ekholm, 1901). However, as the definition for geoengineering adopted in this thesis requires that the intervention have the intention of moderating global warming, the first notable suggestion of geoengineering can be placed at 1965 with the release of the US President’s Science Advisory Committee’s Report ‘Restoring the Quality of Our Environment’ (President’s Science Advisory Committee, 1965).

The report discussed the perils of climate change and stated that ‘possibilities of bringing about countervailing changes by deliberately modifying other processes that affect climate may then be very important’ (President’s Science Advisory Committee, 1965, p. 9). Soon after, on the other side of the Cold War divide, Soviet climatologist Mikhail Budyko published his book Climatic Changes, in which he concluded that ‘climate modification by contemporary technical means can, in theory, be carried out’ (Budyko, 1977, p. 246). Arguably, what then led to geoengineering being considered as a potentially effective action for managing climate change were, firstly the concept of the nuclear winter that surfaced in the 1980s (for example Turco et al., 1983), and then the 1991 eruption of the Filipino volcano Mt Pinatubo. This volcanic eruption injected millions of tons of sulphur dioxide into the lower stratosphere (upper atmosphere), which led to an average cooling of the planet (Hansen et al., 1992). It was ascertained that sulphate aerosols delivered into the stratosphere can scatter incoming solar radiation, reflecting it away from the Earth. In 2006, dismayed at ‘grossly unsuccessful’ attempts to reduce greenhouse gas emissions, Nobel prize-winning chemist Paul Crutzen called for research into ‘adding sunlight reflecting aerosol in the stratosphere’ to cool the Earth’s surface (Crutzen, 2006, p. 212). Crutzen’s article triggered both immediate outrage in the scientific community and the onset of further research (Hamilton, 2013a; Michaelson, 2013). Although Crutzen’s seminal paper was not the first call for geoengineering from the academic community (Oldham et al., 2014), it is often said to be the beginning of scholarship dedicated to this field (Belter and Seidel, 2013).

2.1.2 The technologies

Geoengineering, also referred to as ‘climate engineering’, technologies are often categorised into two broad types: solar radiation management (SRM) options and carbon dioxide removal (CDR) proposals. SRM techniques attempt to alter the ratio of incoming versus outgoing radiation. Cruzten’s call for stratospheric aerosol injection (SAI) is a form of SRM. CDR techniques, also known as ‘negative emission technologies’, aim to remove carbon dioxide (CO_2) directly from the atmosphere via various means.

Methods proposed for SRM have been detailed in numerous papers (Lenton and Vaughan, 2009; National Research Council, 2015a; Royal Society, 2009) but can be broadly characterised as those that decrease incoming solar radiation; those that increase the reflection of shortwave radiation at the level of the stratosphere; and those that increase surface and lower atmospheric albedo. In the first category, for reducing incoming solar radiation, methods proposed involve for example, placing space sunshades in orbit between the Earth and the sun (Angel, 2006), or distributing dust into a cloud around the lunar orbit (Struck, 2007). These types of methods are considered 'impractical at the current time' (National Research Council, 2015a, p. 128) due to costs and technological challenges, but remain an area of interest to a handful of physicists and astronomers.

In the second category, as a means of increasing the reflection of shortwave stratospheric radiation, a prominent proposal is SAI (Crutzen, 2006). As noted, the idea stems from observations of global cooling after natural volcanic eruptions powerful enough to penetrate the stratosphere (Hansen et al., 1992) and seeks to mimic the interruption of solar radiation as a result of volcanic aerosols suspended in the stratosphere (Robock, 2014). SAI research is currently computer-based; it has not been tested in the field at any scale.

In the third category, increasing albedo has been conceived in different forms and at different planetary levels. At ground level, proposals include polyethylene coverings over land (Gaskill and Reese, 2003), bioengineered light-coloured plants and crops (Bala and Nag, 2012; Singarayer and Davies-Barnard, 2012; Wilhelm et al., 2015), and painting urban areas white (Pisello, 2017). At the level of the clouds, an idea that has received growing interest from geoscientists is marine cloud brightening (MCB), which involves seeding low lying clouds to encourage thicker and whiter coverage that is able to intercept incoming solar radiation (Bower et al., 2006; Latham et al., 2014, 2008; Parkes et al., 2012). A number of experiments on marine stratocumulus clouds have taken place (National Research Council, 2015a), and these suggest that additional research is needed before the effectiveness and feasibility of MCB can be established.

CDR techniques aim to 'suck' CO_2 directly from the atmosphere via either biological or chemical processes and occur over different timescales from decades to millennia (IPCC, 2013). Biological CDR methods are either land-based or oceanic and include (but are not limited to) large-scale afforestation, using bioenergy alongside carbon capture and storage (BECCS), and ocean fertilisation. Afforestation, which involves increasing forest coverage in previously unforested areas, is traditionally discussed as a form of emissions reduction because its storage is generally only effective on a scale of decades to centuries (IPCC, 2013). BECCS involves replacing fossil-fuel based energy consumption with bioenergy-based energy consumption and capturing the resultant CO_2 emissions for permanent storage. Especially around issues of land-use, environmental trade-offs and food security, BECCS presents a series of concerns making its social acceptability questionable if deployment becomes widespread (Gough et al., 2018; Stoy et al., 2018). However, climate scenarios with low end-of-century warming assume the use of BECCS at industrial scales (Smith et al., 2016).

Ocean fertilisation involves dispersing across the surface of the oceans elements or compounds (such as iron, nitrogen, phosphate, silica, or urea) that are deficient in that region as a way to stimulate biological growth (Harrison, 2017; Williamson et al., 2012). Another way to do this is through upwelling, which involves circulating nutrient rich waters from the deeper ocean towards the surface (Pan et al., 2018, 2015). Satisfying the nutrient deficiency aims to enhance the primary productivity of the ocean and therefore increase its CO_2 uptake from the atmosphere. In theory, the effectiveness of these methods depends on the level of biological growth and how much of the sequestered carbon is subsequently exported into deeper waters where it should remain for thousands of years (Williamson et al., 2012). In practice, research has produced inconsistent results (Martin et al., 2013; Smetacek et al., 2012) suggesting that efforts may not translate directly into a commensurate increase in long-term carbon sequestration (Robinson et al., 2014).

Chemical CDR methods are of two broad types: enhanced weathering and direct air capture (DAC). Enhanced weathering is the act of accelerating the natural geochemical process whereby the breakdown of silicate rocks locks CO_2 into carbonates that eventually settle on the sea floor (Schuiling and Krijgsman, 2006). It can be done over land (Renforth et al., 2015; Taylor et al., 2017) or over water and involves crushing then dispersing silicate rocks. Carbon storage can be quasi-permanent and can help to alleviate ocean acidification (Taylor et al., 2016). However, the mining, processing, transportation, and dispersal result in a number of damaging environmental effects and require large amounts of energy, likely offsetting any environmental benefits (National Research Council, 2015b). Finally, DAC refers to absorption and adsorption processes to chemically scrub CO_2 from ambient air. The captured and concentrated CO_2 can then be stored geologically or at depths in the ocean (Marcucci et al., 2017; Sanz-Pérez et al., 2016). Various different types and designs of DAC machines have been proposed but none is currently economically viable (National Research Council, 2015b).

Not included in this description of geoengineering technologies is carbon capture and storage (CCS) from a point source, such as a coal-based power plant or an industrial site. Point-source CCS, in this thesis, is considered a form of avoided emissions and therefore fits more comfortably in the category of climate change mitigation. However, CCS associated with bioenergy as part of BECCS, or with DAC, is included in the definition used in this thesis.

The example of CCS helps to highlight the difficulty in clearly defining geoengineering and its demarcations, both from other forms of climate action—such as mitigation and adaptation – and between the categories of SRM and CDR. The SRM/CDR categorisation was first proposed by the Royal Society which decided to group methods in line with their fundamental earth system processes (Royal Society, 2009). This categorisation has become generally accepted in the geoengineering literature (Gupta and Möller, 2018). However, some geoengineering proposals have elements of both categories and others simply do not fit within the SRM/CDR categorisation. For example, afforestation, presented here as a CDR method that is commonly discussed as a form of climate mitigation, also has SRM implications. A large area of sparse earth has high reflectivity, whereas a forest has a dark appearance from space and therefore absorbs more radiation. Afforestation can effectively lower the albedo at surface level and therefore increase the effect of solar radiation. As another example, cirrus cloud thinning (CCT) is a proposed geoengineering method that involves thinning cirrus clouds (the wispy clouds that sit high in the sky) so that more longwave radiation can escape the Earth (Muri et al., 2014). CCT meets the definition of geoengineering but not those of SRM or CDR. Other such examples could exist now or into future.

The key point is that geoengineering is a large and varied assortment of methods, techniques and technologies that are treated as a collective only because they aim to diminish global warming without reducing emissions of greenhouse gases. The focus on this thesis is less on the specific technologies—although their attributes are what shape the debates—and more on the risks and opportunities that they represent. The rest of this chapter, and each of the papers in this thesis, stays with the traditional SRM/CDR distinction when introducing geoengineering and its characteristics. This is for simplicity and to avoid distracting from the central arguments. However, wherever appropriate, the general term ‘geoengineering’ is used and mostly, the issues discussed are typical to geoengineering as a broad category and are applicable to new methods that may be proposed over time.

2.1.3 Geoengineering scholarship

Although relatively young, because of its technological breadth, the entire scholarship of geoengineering cannot be recounted here. Instead a general picture is painted of the different areas of academic interest and their chief advances.

Crutzen’s 2006 paper is said to have triggered scientific curiosity around SAI (for example Robock et al., 2009), and bibliometric studies of the early geoengineering literature seem to support this (Belter and Seidel, 2013; Oldham et al., 2014). Of all proposed SRM methods, SAI has received the most attention from scientists. Research from the natural sciences has covered such topics as the amounts of aerosol required (Kleinschmitt et al., 2018), types of aerosols (Ferraro et al., 2011; Pope et al., 2012; Tang et al., 2014), particle sizes (Rasch et al., 2008), the effect of coagulation (Hommel and Graf, 2011), ideal injection locations (Caldeira and Wood, 2008; Robock et al., 2008; Tilmes et al., 2018), and methods of injection (Davidson et al., 2012; Pierce et al., 2010), but also the potential effects on temperature (Jones et al., 2010; Schmidt et al., 2012) and precipitation (Ferraro et al., 2014; Trenberth and Dai, 2007). The other SRM method of growing academic interest is MCB. However, this research is heavily focussed on improving the currently poor understanding of cloud-aerosol interactions (Latham et al., 2008). Comparatively less research has been published on space-based methods.

Findings suggest that SAI is likely to cool the Earth on average (Kravitz et al., 2013) but that the effects are likely to be regionally disparate (Kravitz et al., 2014). This is because atmospheric greenhouse gases reduce outgoing longwave radiation, which tends to result in a warmer and wetter climate overall, whereas SAI reduces incoming shortwave radiation, so the overall effect on evaporation, latent heat flux and therefore precipitation is complex; it does not simply counter the precipitation impacts of increased greenhouse gases. Nonetheless, no region is likely to be further from pre-industrial temperatures as result of SAI, compared to continued warming (Kravitz et al., 2014). The hydrological cycle is likely to be affected by SAI (Niemeier et al., 2013; Trenberth and Dai, 2007) and the effects on rainfall are hard to predict regionally but are likely to result is less rain globally on average, compared to continued warming (Kravitz et al., 2013). Reduced sunlight is also likely to affect the yields of staple crops such as maize, soy, rice, and wheat (Proctor et al., 2018). And modelling has been carried out on what is known as the ‘termination effect’, which describes sudden warming after an SAI project is abruptly halted for any reason (Jones et al., 2013; Matthews and Caldeira, 2007). This research suggests that to avoid rapid warming rates any venture into SAI would need to be part of a long-term plan (Keith and MacMartin, 2015). Questions on how SAI might be deployed—whether by fleets of aircrafts, tethered balloons, or pipes – and the engineering details of such operations are less well studied, but economic analyses suggest that deployment could be designed to be affordable and quick (National Research Council, 2015a). However, SAI would do nothing to alleviate other effects of climate change such as ocean acidification. As a result, SAI is often said to be ‘cheap, fast and imperfect’ (Keith et al., 2010, p. 426). Due to the complexity of interconnected Earth and climate systems, a high level of uncertainty remains around what SAI could do, how it could do it, and what could go wrong, both from technical and social perspectives. There is therefore much fertile ground for further research.

CDR scholarship began earlier than 2006 with a number of ocean fertilisation experiments that took place from 1993 (Boyd et al., 2007; Williamson et al., 2012). Research covers such topics as types of nutrients added (Lampitt et al., 2008), likely effectiveness (Denman, 2008; Gnanadesikan et al., 2003; Levasseur et al., 2006), potential adverse effects (Cullen and Boyd, 2008; Lawrence, 2002), costs (Rickels et al., 2009), and global capacity (Aumont and Bopp, 2006), and findings suggest that ocean fertilisation, while still attracting research funding, is not likely to be as effective as originally estimated and that serious ecological concerns are yet to be resolved (National Research Council, 2015b). Land-based CDR methods have also been the focus of academic discussions in the geoengineering space (Belter and Seidel, 2013). Mostly research covers the science of such methods (Keller et al., 2018a; National Research Council, 2015b), their capacity to moderate climate change (Boysen, 2017; Psarras et al., 2017; Smith et al., 2016), potential adverse impacts (Boysen et al., 2016; Heck et al., 2016; McCormack et al., 2016), costs (Fuss et al., 2018; Heutel et al., 2016), and social implications (Buck, 2016). In general, the literature finds that CDR methods are likely to contribute variously to action on climate change but the annual global CDR potential, ignoring engineering, economic and social constraints, is currently less than 20% of annual carbon emissions (Lenton, 2014). In contrast to SAI, it can be said that CDR techniques are likely to be more costly, slower-acting and geographically distributed, raising different concerns to those of SAI.

A key and growing emphasis in the geoengineering literature is governance: given the range of potential benefits and risks from proposed methods, how can governance be designed to manage social, political, and ethical concerns? This literature includes discussions of whether some geoengineering proposals are at all governable (Hamilton, 2013b; Hulme, 2014; Macnaghten and Szerszynski, 2013) and the ethics of progressing with such ideas (Lenzi, 2018; McLaren, 2018; Morrow, 2014; Preston, 2017; Svoboda, 2017); how geoengineering concepts are received by the media, civil society or communities (Bellamy et al., 2017; Buck, 2013; Burns et al., 2016; Carr and Yung, 2018; Corner and Pidgeon, 2014a, 2014b; Luokkanen et al., 2013; Porter and Hulme, 2013; Scheer and Renn, 2014; Sütterlin and Siegrist, 2017; Tingley and Wagner, 2017; Visschers et al., 2017); how human rights are likely to be affected (Adelman, 2017; Burns, 2016; Svoboda et al., 2018) and the relevance of humanitarian systems in this (Suarez and van Aalst, 2017); relevance to climate governance (Fuglestvedt et al., 2018; Haszeldine et al., 2018; Kurosawa et al., 2017; MacMartin et al., 2018) and legal analyses of how existing multilateral agreements might cover proposed geoengineering interventions (Bodle et al., 2014; Humphreys, 2011; Lin, 2009; Lloyd and Oppenheimer, 2014; Virgoe, 2009); and whether or how to continue geoengineering research while governance is being discussed (Bellamy, 2016; Dilling and Hauser, 2013; Keith et al., 2010; Lin, 2015; Parker, 2014; Stilgoe, 2015). As noted by Gupta and Möller (2018, p. 2):

> The vast majority of [geoengineering] governance analyses focus on debating what (…) norms, institutional arrangements and rules could or should be, usually accompanied by description of the few formal governance arrangements that do exist.

Unsurprisingly, given the high-stakes of both unmitigated climate change and potential geoengineering deployment, the governance literature suggests contested and highly polarised views of geoengineering (Kreuter, 2018). A case in point, in 2013 Harvard physicist David Keith published a small red book entitled ‘The case for geoengineering’, in which it is argued on largely technical grounds that while geoengineering is not an ideal outcome, it may become a least-worst and economically sensible option (Keith, 2013). In response, in 2014 Cambridge human geographer Mike Hulme published a small blue book entitled 'Can Science Fix Climate Change: A Case Against Climate Engineering', in which it is argued that geoengineering can be an answer only if the wrong question is asked (Hulme, 2014). Such spectrally divergent approaches to geoengineering debates are often framed as those of either Gaian or Promethean ideal types (Anshelm and Hansson, 2014; Hamilton, 2013b; Thiele, 2018). And as Thiele (2018) explains, 'Prometheans and Gaians typically talk past each other' (2018, p. 1)—as a result, finding common ground upon which to progress geoengineering governance discussions is challenging.

2.2 Governing geoengineering for sustainability

Thiele (2018) proposes that one way for polar-opposites in the geoengineering debate to communicate is through the concept and language of sustainability, which can act as a bridge between ends of the Prometheus-Gaia spectrum. Geoengineering features all the characteristics of a globally significant post-normal problem of sustainability (Funtowicz and Ravetz, 1994; Miller et al., 2014; Rittel and Webber, 1973): a high level of complexity in the science, leading to irreducible uncertainty that is conflated with contested values and divergent worldviews; high stakes in the long-term and potentially devastating nature of geoengineering decision-making, combined with the impossibility of individual opt-outs; and a growing urgency exhibited daily in rising atmospheric concentrations of greenhouse gases. Although the literature includes discussions of these challenges from a number of viewpoints—including justice perspectives (McLaren, 2018), human rights perspectives (Burns, 2016), ethical perspectives (Gardiner, 2013; Svoboda, 2017) and economic perspectives (Bickel and Agrawal, 2013)—that sometimes incorporate sustainability values as foundational elements, there has been little focus on geoengineering explicitly from a sustainability science perspective. A notable exception comes from Sugiyama et al. (2016) who undertook a deliberative process to identify socially-relevant geoengineering research within a sustainability science framework—a first step in filling a gap in the geoengineering literature.

This subsection provides a background to the concept of sustainable governance (as it is understood in this thesis), which is founded on interpretations and re-interpretations of notions of governance, sustainable development, sustainability and sustainability science.

2.2.1 From sustainable development to sustainability science

The idea of sustainable development proposes that the human needs of economic security and stability, plus social equality and wellbeing, and the environmental needs of ecological health and integrity are interdependent and necessary features of enduring global societies. The term 'sustainable development' was first defined in 1987 in the World Commission on Environment and Development's report 'Our common future' as development that 'meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987, p. 26). The idea that unchecked growth in population, resource consumption, and economic activity could not occur indefinitely without permanently disrupting ecological systems were first suggested well before the term 'sustainability' was popularised (Carson et al., 1962; Meadows, 1972), but global concern was ignited over increasing evidence of transboundary pollution, environmental degradation, and unequal levels of affluence (Kemp et al., 2005), brought to light at the 1972 UN Conference on the Human Environment. Over the last decades, the creation of multiple international environmental agreements—Agenda

21, the UNFCCC, the Convention on Biological Diversity, and others—has been founded on the concept of sustainable development.

Despite such strong political enthusiasm for the concept, its meaning is forever disputed (Martens, 2007; Pezzoli, 1997). Criticisms of sustainable development relate to its ambiguity on the one hand (Martens, 2007; Mebratu, 1998) and its oxymoronic nature on the other (Robinson, 2004). What is meant, practically, by the concept? If both poverty and economic growth are linked to environmental problems, how then can development ever be sustainable? Proxies used to assess sustainable development are limited and debatable (Pogge and Sengupta, 2015; Sengupta, 2018); so how can sustainable development be implemented to meet objective criteria? These criticisms have led to a shift in the terminology, at least in academic circles if not in government and the private sector, towards 'sustainability' rather than 'sustainable development' (Robinson, 2004). However, sustainability too remains a fuzzy and disputed concept (Kuhlman et al., 2010).

Since the late 1990s a new arena of research has emerged dedicated to enabling a transition to sustainability (Komiyama and Takeuchi, 2006). Sustainability science is the study of 'interactions between nature and society and on society's capacity to guide those interactions along more sustainable trajectories' (Kates et al., 2001, p. 641). To achieve this goal, sustainability science has come to be guided by a number of principles. It adopts a systems perspective as a means to appreciate the complex nature of interactions between self-organising Earth and human systems (Kates et al., 2001; Martens, 2007). In doing so, it studies phenomena across spatial, temporal, and other scales, including scales of jurisdiction and knowledge (Cash et al., 2006; Kates et al., 2001; Swart et al., 2004; Thomas et al., 2018); it is problem-driven and solution-oriented (Clark and Dickson, 2003); and it adopts inter- and transdisciplinary approaches that bridge social and natural science perspectives (Lang et al., 2012); but also co-creating knowledge with practitioners (Clark and Dickson, 2003; Lang et al., 2012; Martens, 2007) to promote social learning (Miller et al., 2014).

Transformational sustainability science pursues four types of knowledge. Descriptive-analytical knowledge (or knowledge on perceived realities) helps to understand problems within the paradigm of a human-environment dynamic system, drawing on methods and analysis from diverse disciplinary approaches (König, 2018; Wiek and Lang, 2016). An example of this kind of research might be understanding how geoengineering threatens planetary boundaries (Rockström et al., 2009a; Steffen et al., 2015). Normative knowledge (or knowledge on values) helps to identify and recognise different worldviews and contested value-sets regarding environmental or social change (Christen and Schmidt, 2012; König, 2018; Wiek and Lang, 2016). An example of this type of research might be to investigate public views on acceptable goals for geoengineering and therefore what trade-offs might be tolerable in its deployment. Anticipatory knowledge (or knowledge on futures) helps to understand various ways that a system might develop or evolve (König, 2018; Wiek and Lang, 2016). Two types of anticipatory knowledge can be generated: knowledge about key determinants and uncertainties that have the capacity to define the future; and knowledge on what might be desirable in the future and how to steer in that direction. An example of anticipatory knowledge is undertaking visioning exercises to determine what a sustainable geoengineering future might resemble. Finally, actionable knowledge helps to advise strategy and policy. This type of research not only seeks implementable solutions, but it does so in collaboration with stakeholders to ensure that the proposals are legitimate and have the necessary buy-in (König, 2018; Wiek and Lang, 2016). An example of actionable research might be a participatory geoengineering workshop that engages stakeholders on ways to avoid polarising the geoengineering debate in Australia (as has been seen for climate change).

The challenges that sustainability science tackles are complex and often confront societal hopes and desires. The 'wicked problems' (Rittel and Webber, 1973) of climate change, ocean acidification, ozone depletion, biodiversity loss, chemical pollution, and freshwater scarcity are examples of sustainability challenges (Rockström et al., 2009a). Technological innovations are also interesting research fields for sustainable governance research. Nanotechnology (Wiek et al., 2007), synthetic biology (Wiek et al., 2012a), and blockchains (Vranken, 2017) have, for example, been the foci of sustainability research. However, geoengineering remains an underexplored field of sustainability science research.

2.2.2 Sustainable governance

Within its mandate of producing transformational and actionable knowledge, sustainability science ventures also into the realm of governance theory. Scholarship on sustainable governance is nascent and the infrequency of references to 'sustainable governance' in the academic literature suggests that it has yet to establish its merit.

Just as the concept of sustainability is ill-defined and ambiguous, so too is the concept of governance. A generic but useful starting point is provided by Stoker (1998, p. 17) who explains that '[g]overnance is ultimately concerned with creating the conditions for ordered rule and collective action'. Until the late twentieth century, this tended to refer wholly to the actions of government. However, governance as we use the term today (emerging from political sciences in the United States and United Kingdom after the 1980s) tends to refer to more than just government (Bevir, 2008; Rhodes, 1997a). It is broader. Where previously it meant a hierarchical and state-centric arrangement, it now can refer to self-regulating networks and to collaborations between interdependent state and non-state stakeholders with interrelated interests (Kooiman, 1993; Newman, 2001; Rhodes, 1996). The role of government has thus shrunk—or perhaps shifted (Kooiman, 2003)—back to its etymological meaning of steering or navigating (Osborne and Gaebler, 1993).

Governance is effective in different ways at different levels (Pierre and Peters, 2000). As there is no central and supreme world authority, global governance is by necessity the project of multiple actors. Key actors are generally categorised as state-driven, corporate or civil society; and the mechanisms of governance tend to be traditional forms of black-letter law, but also 'softer' methods such as financial incentives or the establishment of unwritten norms. At the global level, sustainability issues, specifically environmental issues that pose transboundary or collective action concerns, have been triggers for, and manifestations of, new perspectives (Young, 1997), in an age identified by some as the Anthropocene (Steffen et al., 2011). According to Heinrichs and Bierman (2016, p. 134), globally 'the discourse on environmental policy and governance has been (…) developed into a new perspective that takes the entire Earth system as an object of political efforts: "Earth system" governance'.

ESG is a social science research program that explores 'how to reform the ways in which human societies (fail to) steer their coevolution with nature at the planetary scale' (Heinrichs and Biermann, 2016, pp. 134–5). It is built around an analytical framework with five interlinked dimensions and four cross-cutting themes. The five dimensions of ESG, of its systems and of its mechanisms are its architecture, its adaptiveness, its accountability and legitimacy, the agency of its players, and its effective allocation and access. The four themes of social sciences relevant to these five dimensions are power, knowledge, norms and scale (Biermann et al., 2010). Scholars in the ESG community draw on this framework to appreciate how human societies are exerting irreversible pressures on Earth systems and to propose governance reforms that can redirect human activities towards planetary stewardship (Biermann et al., 2012).

At the national or more local level there is more elasticity in the definition of governance depending on the system under analysis. It is a social paradigm of decision-making that incorporates and serves the competing interests of its stakeholders, many of which have been institutionalised into communities or interest groups (Parker and Braithwaite, 2005). Ison et al. (2014) provide a useful definition of governance by linking it to its ultimate outcome:

> …governing encompasses the totality of mechanisms and instruments available for influencing social change in certain directions including a practitioner's own history (ie, identity). Whether purposeful or not, the collective activities of governance produces effects comprising varying degrees of coordination or lack of coordination, control or loss of control, and certainty or uncertainty. The point is to arrive where a loss of control does not lead to fear but to social learning and innovation (Ison et al., 2014, p. 626).

What do we, as a society, want from governance? If sustainability is the desired outcome, then sustainable governance is the means. Costanza et al. (1998) defined sustainable governance, specifically in response to anthropogenic pressures exerted on the oceans, according to six key principles: responsibility, scale-matching, precaution, adaptive management, full cost allocation, and participation. Although this definition draws on some of the dimensions of sustainability, it does not address them all. A definition from Shiroyama et al. (2012) describe sustainable governance as 'formal and informal networks/interactions among actors, and systems composed by them, that influence sustainability by integrating various dimensions' (2012, p. 46). Wiek et al. (2009) add to this definition explaining that sustainable governance covers 'the whole decision-making and policy cycle from knowledge generation to taking actions, as well as controlling, evaluating and adjusting them' (2009, p. 285):

> A core component of the governance cycle is the creation of reliable and salient knowledge, including good understanding of (a) how the socio-technical system functions (analytical); (b) how the system could evolve (anticipatory); (c) what would be positive/negative impacts, and how the system should evolve (normative); (d) what would be precautionary and protective measures to avoid undesirable developments (action-oriented).

Within the normative framework of ecosystem diversity and health, human and social wellbeing, and justice and equity over space and time (Dresner, 2002), sustainable governance thus involves participatory and inclusive processes as means to: understand the governance system, its main elements, how these interrelate, and what is their history (descriptive-analytical research); appreciate where the system may be headed without intervention (anticipatory research); consider what a preferred outcome might resemble (normative research); and devise methods to steer the trajectories towards sustainable futures (transformative/action-oriented research) (Wiek et al., 2011). Figure 2.1, adapted from Wiek et al. (2013, p. 55) is a schematic of transformational sustainability science as it relates to geoengineering governance.

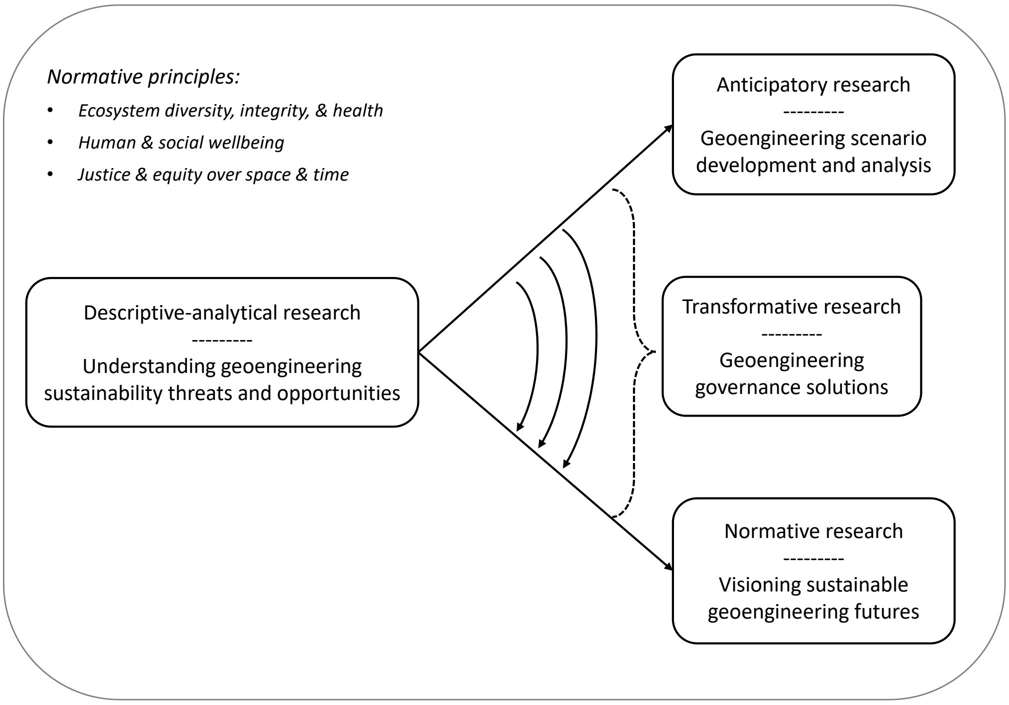

Figure 2.1: Sustainable geoengineering governance research framework (adapted from Wiek et al., 2013, p. 55)

Sustainable governance scholarship has explored such policy domains as forest degradation (Mathez-Stiefel et al., 2017; Shiroyama et al., 2012), water management (Decamps and Barbat, 2017), organic food production (Han et al., 2017), global phosphorous management (Shiroyama et al., 2012), and emerging technologies broadly (Shiroyama, 2013; Wiek et al., 2009), plus nanotechnology (Wiek et al., 2008, 2007) and synthetic biology (Wiek et al., 2012a) specifically, but not geoengineering.

2.3 Scenarios for sustainable governance

2.3.1 Scenarios for foresight

A key element of sustainable governance is foresight. Foresight is yet another term for which there can be, and are, many different interpretations (Sardar, 2010). Most simply, Fuerth (2009, p. 16) suggests that '[f]oresight is the capacity to anticipate alternative futures, based on sensitivity to weak signals, and an ability to visualize their consequences, in the form of multiple possible outcomes'. Amanatidou (2014) provides a more wide-ranging description, suggesting that whatever the definition for foresight, it is action-oriented and multi-disciplinary, facilitating structured anticipation, creative thinking, interaction, participation and collective learning. One point of agreement across the academic literature, if not in common-use language, is that foresight is not forecasting (Eriksson and Weber, 2008). Where forecasting offers a deterministic singular view of the future, foresight offers mere insight into a range of futures (Sardar, 2010). A central theme is that foresight exists only insomuch as it affects decision-making (Eriksson and Weber, 2008) by allowing and embedding methods for reflexivity (Barben et al., 2008).

> As a factor in governance, the purpose of foresight is to enhance the ability of decision-makers to engage and shape events at a longer range and, therefore, to the best advantage of the citizens they serve (Fuerth, 2009, p. 17).

In practical terms, foresight activities are merely thought experiments set in the future (Karlsen and Karlsen, 2013). These were originally undertaken specifically in the field of innovation and technology to identify 'areas of strategic research and emerging generic technologies likely to yield the greatest economic and social benefits' (Martin, 1995, p. 140), but foresight is currently used in a broader range of applications and in diverse ways. Foresight exercises can be qualitative, quantitative, or semi-quantitative (Popper, 2008) and can be designed to incorporate or to draw on varying levels of creativity, expertise, interaction, and evidence (Popper, 2008). Examples include backcasting, science fictioning, scenarios, citizen panels, expert panels, morphological analyses, life cycle assessments, delphi methods, SWOT analyses, future-oriented bibliometrics, roadmapping, cross-impact analysis, technology assessments, modelling, and logic diagrams (Barben et al., 2008; Popper, 2008).

Scenarios are a popular tool of foresight, and for some synonymous with foresight (Barben et al., 2008). Scenarios are stories of how the future could evolve (Schoemaker, 1991). They draw on understanding of a system's history, its key components and how these are connected to other systems (Schwartz, 1991). Scenarios are particularly useful when an issue is complex, uncertain, and dynamic (Wilkinson et al., 2013). By making alternate future pathways tangible, scenarios are ways to illustrate different perspectives from which a decision can be considered and to appreciate the potential ramifications of such decisions (Wilkinson, 2009). The history of scenarios dates back to the 1950s as part of American Cold-War national security efforts (Kahn and Wiener, 1967), and the 1970s as part of strategic corporate investment planning at the Royal Dutch Shell company (Wack, 1985a), but scenarios experienced a resurgence and gained a new purpose as the sustainable development movement began (Swart et al., 2004).

Computer simulated scenarios underpinned the Limits to Growth movement; they were used to argue that, unless curtailed, humanity and human activities were likely to overwhelm environmental resources within 100 years (Meadows, 1972). Since then, scenarios have provided a basis for, and link between, scientific research and policymaking in sustainability. A salient example is the reliance on the scenarios developed by IPCC for international climate change negotiations under the UNFCCC. Scenarios were first developed by the IPCC in 1990 as part of the First Assessment Report (the SA90 scenarios), and there have subsequently been four new iterations—the IS92 scenarios of 1992, the Special Report on Emissions Scenarios (SRES) of 2000, the Representative Concentration Pathways (RCPs), and the Shared Socioeconomic Pathways currently under development[1] (Moss et al., 2010). Scenarios have always been at the heart of climate change policymaking (Alcamo, 2008a).

2.3.2 The different roles of scenarios

The greenhouse gas emissions or concentration stabilisation scenarios of the IPCC are useful in creating a safe space to alter assumptions and test theories to progress scientific knowledge. However, they represent just one

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[1] There was one additional iteration before the RCPs, known as the post-SRES; this family of scenarios was essentially a subset of the SRES.

specific type of scenario that is quantitative and descriptive. Many other types exist, and these can be categorised in several ways. Mitchell et al. (1979) suggest that scenario techniques can be broadly categorised as either heuristic procedures; simulation and gaming techniques; or programming tools with analytical techniques that fit within—or crossover between—those three broader groupings. Börjeson et al. (2006) identify three categories of scenarios differentiated as predictive, exploratory or normative. Rounsevell and Metzger (2010) list six distinct scenario methods as exploratory, normative, business-as-usual, participatory, probabilistic, and scaling methods. Bishop et al. (2007) propose eight functional categories or types of scenario methods that encompass more than 20 individual techniques between them. Van Notten et al. (2003) catalogue 14 scenario types divided into three overarching themes that consider the project goal, its design, and the content of the scenarios. For Ducot and Lubben (1980) there are 27 different approaches, as defined by three dimensions regarding the purpose of the exercise, the significance of cause-effect relationship, and the likelihood of certain scenarios.

Determining the right type of scenario is done based on the purpose of the foresight exercise. In environmental assessments the purpose of scenarios is often to understand physical processes, to anticipate potential environmental impacts, and to inform resource management (Alcamo, 2008b). These types of scenarios are designed as experiments to be run on supercomputers and are sometimes referred to as ‘story and simulation’, where ‘storylines about how relevant events might unfold in the future are used to parameterize models of biophysical and social processes, each consistent with an alternative future’ (Garb et al., 2008, p. 1).

Geoengineering research, as inherently linked to climate change research, also relies on these types of scenarios, for example to understand regional impacts of geoengineering proposals. To this end, the geoengineering research community has developed families of geoengineering experiments, the first of which were known as the Geoengineering Model Intercomparison Project (GeoMIP). The GeoMIP began as four computer-modelling scenarios—known as G1, G2, G3 and G4—of standardised SRM simulations to maximise attribution and minimise uncertainties when comparing results from different climate models (Kravitz et al., 2011), and has since been extended to add more technology types and experiments (Kravitz et al., 2015). Some of these are built on the IPCC RCP scenarios, for example in G3 and G4, SRM is simulated against the background of RCP4.5. The GeoMIP scenarios represent a large portion of the geoengineering scenarios literature, and recently a set of CDR scenarios was proposed, known as CDRMIP (Keller et al., 2018b). GeoMIP scenarios have been used to study, for example, regional effects of SRM (Yu et al., 2015), hydrological impacts (Tilmes et al., 2013), implications for Arctic sea ice (Moore et al., 2014), impacts on agriculture and vegetation (Glienke et al., 2015; Xia et al., 2014), and the termination effect (Jones et al., 2013).

However, scenarios need not be quantitative computer modelling tools. Sometimes the purpose of the exercise is not supported by the use of quantitative scenarios, or there may not be the data to generate quantitative scenarios (van Notten et al., 2003). Qualitative and participatory scenarios, where stakeholders are brought together to collaborate in the creation of scenarios through negotiation and shared learning, are useful where the objective of the exercise is to reveal implicit assumptions about the present and the future, to expose threats and opportunities, and to provide a shared platform for debate as a way to improve communication between stakeholders (Huss, 1988). Qualitative and participatory scenarios can ‘help us to work with different kinds of knowledge, ignorance and uncertainty’ (Wilkinson and Eidinow, 2008, p. 3) thereby adding legitimacy to the exercise, increasing the credibility of the outcome, and improving implementation (Richards et al., 2004;

Volkery et al., 2008). Yet these types of scenarios maintain a contentious place in academia as a 'practice-led field' (Wilkinson et al., 2013, p. 704).

Other criticisms of exploratory participatory scenario approaches include its time-consuming nature and inexact science that requires constant trade-offs between feasibility and rigour (Molitor, 2009). Where assumptions are made to simplify a process, the exercise can be criticised for those assumptions and for the omission of critical factors (Schoemaker, 2004). Another major critique is that it is difficult to validate the usefulness of scenarios (Jungermann, 1985). One might assume that a good scenario has real predictive value, but the inexistence of future data against which to corroborate scenarios renders this type of independent appraisal impossible (Rounsevell and Metzger, 2010). Further, the future may have been 'shifted' from one possible trajectory onto another because of insight gleaned from a scenario.

2.3.3 Scenarios in sustainability science

Despite these limitations, it can be argued that 'the rise of scenario analysis across spheres would be interpreted as evidence of its utility' (Garb et al., 2008, p. 4) (although such a statement calls for a level of critical analysis). And scenarios have become an important part of 'steering and coordinating large-scale system innovations towards greater sustainability' (Sondeijker et al., 2006, p. 15).

An objective of sustainability science is appreciating the broad range of futures that could result from the interaction of human and ecological systems both of which are shrouded in uncertainty and complexity (Funtowicz and Ravetz, 2003). Scenarios, where they combine different types of knowledge, where they methodically survey entries to potential future pathways, and where they link social decisions to their environments, can provide crucial platforms for sustainability science. 'While scenario analysis cannot provide, of course, all the answers to the questions posed by sustainability science, it has an important role to play in synthesis, thinking about the future, and linking to policy and stakeholder communities' (Swart et al., 2004, p. 143).

Again, different types of scenarios are suited to different types of sustainability problem-solving. Exploratory scenarios—where scenarios are based on changing a limited number of a key determinants and exploring the likely outcomes—are useful for revealing discontinuities, surprises, tipping points, and early warning signals to inform policy-making and natural resource management (Haasnoot and Middelkoop, 2012). Backcasting—defined as 'generating a desirable future, and then looking backwards from that future to the present in order to strategize and to plan how it could be achieved'(Vergragt and Quist, 2011, p. 747)—is useful for understanding the link between sustainability risks and opportunities of the present and those of the future and for investigating ways to alter the trajectory of human and environmental systems (Quist and Vergragt, 2006; Swart et al., 2004). Descriptive scenarios—which simply state 'an ordered set of possible occurrences, irrespective of their desirability or undesirability' (Ducot and Lubben, 1980, p. 52)—are useful for opening up normative discussions about worldviews, hopes, and desires to facilitate the incorporation of cultural and social values into decision-making.

An important aspect of scenarios, especially scenarios as part of sustainability science, is that they are not passive objects of research (Selin, 2007). Their use, form, underlying assumptions, findings, and communication must be carefully considered as these have implications for sustainable governance by creating or perpetuating expectations (Borup and Konrad, 2004; Brown, 2003). As noted by Stilgoe (2016, p. 852), 'geoengineering has been naturalised by its researchers, treated as a thing in the world to be understood rather than a highly controversial, speculative set of technological fix proposals'.

Although scenarios have been, and likely will remain, key tools of geoengineering research, it is only recently that studies have emerged scrutinising the shape and content of these scenarios and their implications. In an anecdotal study of SRM climate modelling scenarios in which the modellers were interviewed, Wiertz (2015, p. 3) found that 'climate models have been turned into ''inventive tools,'' allowing scientists to develop and refine speculative technological concepts and to envision novel ways of climate control and optimization'. Instead of scenarios being used to investigate and better understand the climatic and environmental effects of different technological designs for SRM, they are setting standards and motivating engineers to achieve certain objectives. This is problematic because climate models are simplifications of highly complex dynamic systems. Parameters that are most easily altered in computer simulations are not necessarily adjustable in reality. As a result, expectations about what SRM could look like and deliver are more closely related to the vision and skill of the modelling team than what might be technically possible (Wiertz, 2015).

This is also problematic because expectations about the range of solutions can frame how the problem is conceived. Commenting on the role of integrated assessment models in shaping science and policy agendas, Low (2017) notes that questionable assumptions about the widespread availability and use of CDR (specifically BECCS) for achieving low end-of-century global average temperatures have come to 'anchor[s] expectations and motivate[s] actors in climate governance' (Low, 2017, p. 69). Similarly, Sugiyama et al. (2017) call attention to the tendency for economic models to promote scenarios in which SRM use is maximised, simply because the cost is relatively low compared to mitigation options. This results in the expectations that SRM deployment is likely to undertaken to its maximum capacity. At the same time, climate model scenarios tend to use strong SRM forcings to demonstrate the termination effect. This, Sugiyama et al. (2017) suggest, has led to a blinkered understanding of SRM deployment as an option that can only be large-scale and long-term. They suggest instead that 'quantitative scenario research should encompass a wide range of relevant uncertainties and policy choices' (Sugiyama et al., 2017, p. 3). What is also needed is an understanding of the specific ways in which existing geoengineering scenarios frame assumptions about the technologies and create expectations for researchers and society.

2.4 Australia's place in the geoengineering debate

The geoengineering research literature consists predominantly of publications from English-speaking industrialised countries in the Northern Hemisphere (Belter and Seidel, 2013). The focus of research is thus either high-level and global, or directed at the Northern Hemisphere specifically. Yet the possible impacts of climate engineering on the Southern Hemisphere may be different from the rest of the world and the risks and opportunities that climate engineering methods present Australia may be unique.

2.4.1 Geoengineering impacts on Australia

There is poor understanding of the potential impacts of most geoengineering proposals for Australia or for the Southern Hemisphere. Where increasing such understanding may be particularly relevant is in relation to proposals that are either highly localised, such as ocean fertilisation, or proposals that are global but are expected to have different regional effects, such as SAI.

As noted, there has been some support for and interest in Australian research on ocean fertilisation because the 'Southern Ocean contains the largest area of iron-limited conditions' (National Research Council, 2015b, p. 58). Regional studies such as those in the Southern Ocean, have focussed on the scientific robustness of the methods and their effectiveness rather than specific risks to local ecosystems. Generally, it has been found that the ecological effects of ocean fertilisation on fisheries and the marine food web may be considerable but are poorly understood. 'It is also likely that iron fertilization will have downstream effects on nutrient supply, and thus productivity and food web dynamics, in other ocean regions' (National Research Council, 2015b, p. 61).

As no SAI impact study focusses exclusively on Australia, relevant data can be gleaned only from results of more general research. Irvine et al. (2010) undertook computer simulations reducing the solar constant as a proxy for SAI. The findings illustrated notable differences between Northern and Southern Hemisphere impacts—cooling effects were found to be more pronounced at higher latitudes—and suggested that the Australian climate could return some way to pre-industrial levels with some degree of SAI. A study by Jones et al. (2010), comparing outputs from climate models featuring the injection of aerosols (sulphur dioxide) into the stratosphere at a constant rate over some period and then abruptly terminated, found that the distribution of aerosols tended towards higher latitudes. Models showed that when the global-mean temperature anomaly from SAI is zero, Australia (and central Africa) is cooler by up to one degree Kelvin. Kravitz et al. (2014), using the output from 12 models simulating scenarios similar to those of Irvine et al. (2010), found that with up to 90% of solar radiation offset, temperatures in all global regions (a total of 22) return towards pre-industrial levels (beyond 90% this no longer holds). The study also found that for precipitation there is no optimal level of radiation offset—whenever rainfall increases in some regions it decreases in other regions. Investigating the trade-offs between precipitation and temperature, the study could not determine a level of solar radiation offset for which both temperature and precipitation were closer to pre-industrial levels for all regions. Most recently, Jones et al (2018) found, using a coupled atmosphere–ocean global climate model, that with equal aerosol injection rates in the Northern and Southern Hemispheres, the change in (sulphur dioxide) aerosol optical depth was greater in the Northern Hemisphere and resulted in a more uniform sulphate distribution than in the Southern Hemisphere. The non-uniformity of SAI responses highlights the importance for decision-making of understanding both the potential impacts and related uncertainties for Australia.

2.4.2 Australian engagement on geoengineering

To date, Australia's contribution to climate engineering policy discussions and research domestically has been minimal. The first Garnaut Review of 2008, which took more than 600 pages to 'consider policies that: mitigate climate change, reduce the costs of adjustment to climate change ... and reduce any adverse effects of climate change and mitigating policy responses on Australian incomes' (Garnaut, 2008, p. xvi), dedicated just one page to climate engineering. The updated Garnaut Review of 2011 paid even less attention to climate engineering, making a few mentions while not addressing the topic directly (Garnaut, 2011). The Climate Commission, which was Australia's Government-supported independent and reliable source of information 'on climate change science and impacts, and international action' (The Hon Greg Combet, 2011), never once mentioned climate engineering. The Australian Government's only contribution to the literature on climate engineering is the Office of the Chief Scientist's four-page paper on the fundamentals of climate engineering technologies in its Occasional Paper Series published in April 2012 (Reekie and Howard, 2012).

In late-2010 the Australian Academy of Sciences' National Committee for Earth System Science (NCESS) published a report 'To live within Earth's limits: An Australian plan to develop a science of the whole Earth system'. In that report the NCESS posed the question: 'As a complement to greenhouse gas emission mitigation, how can Australia engage in global considerations of responsible geo-engineering options?' (Gifford et al., 2010, p. ix). Within that context, in 2011 the Australian Academy of Sciences organised a symposium entitled 'Geoengineering The Climate? A Southern Hemisphere Perspective'. The symposium brought together natural scientists interested in oceans, forests and the atmosphere, but also engineers and social scientists. Although representatives of Federal and State governments were present at the event, they did not feature on the symposium's list of speakers. As the next stage, in 2018, the NCESS is hosting the 'Negative Emissions Conference: The big picture of negative emissions' to explore and discuss CDR options and their viability.

From civil society there have been isolated examples of engagement. The Climate Institute published a report entitled 'Moving Below zero: Understanding Bioenergy with Carbon Capture and Storage' (Pinder, 2014). The Australian Breakthrough Institute started urging the government to adopt a 'safe climate' strategy (Sutton, 2015) that involves 'not just a slowing or stabilisation of the warming, but instead a cooling of the earth to below its current temperature' (Spratt, 2016, p. 15). Outspoken author and academic, Clive Hamilton, published in 2013, 'Earthmasters: Playing God with the Climate', a book that defines the technologies, geopolitics and ethics of climate engineering as direct attacks on what it means to be humans on planet Earth (Hamilton, 2013b). Australia's once Chief Commissioner to the government's Climate Commission, Tim Flannery, published a book describing the 'third way' to deal with climate change (Flannery, 2015), consisting of variety of methods that 'shed light on how Earth's natural system for maintaining the carbon balance might be stimulated to draw CO_2 out of the air and sea at a faster rate than occurs presently' (2015, p. xvii). Extreme examples included running immense air conditioners in Antarctica to cool the air to the point that CO_2 'snows' right out of the sky, and extensive seaweed farming as feedstock for floating methane digesters.

In international marine engineering deliberations, Australia has played a relatively active role. In 2013, Australia led a proposal to amend the 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes or other Matter to include marine geoengineering (International Maritime Organization, 2013a). The amendments were adopted but few countries have lodged instruments of acceptance (Australia has not) and therefore the amendments are yet to come into force. Should they do so, marine geoengineering activities—which are defined by a list in an annex to the treaty—will be banned except for 'legitimate scientific research' (International Maritime Organization, 2013b).

On the floor of the Australia's Parliament, or within its committees, there have been only three mentions of the term 'geoengineering': one as part of an attempt by a climate denier to undermine the science of climate change in 2009 (Jensen, 2009), one in relation to a 2018 citizen petition that had the flavour of a conspiracy theory ("Petitions - Climate - Procedural text," 2018); and one in response to the petition, where the Minister for the Environment and Energy simply referred the constituent back to the government's aforementioned actions in international marine pollution negotiations (Frydenberg, 2018).

Yet, Australian research into marine geoengineering progresses. In 2015, the Australian Research Council awarded a AU$2.5 million grant under the Australian Laureate Fellowships to the University of Tasmania to investigate the scientific and economic feasibility of marine geoengineering in the Southern Ocean and to inform Australian and international geoengineering policy (Australian Research Council, 2016). In separate funding announcements, the Federal and Queensland governments have announced a series of projects aimed at reducing the pressures of climate change on the Great Barrier Reef, at least two of which—MCB (Ellis-Jones, 2017) and ocean upwelling (RRRC, 2017)—can be clearly classified as geoengineering.

Whether Australia's efforts in the marine geoengineering science and policy arena are indicative of a coherent national and international Australian policy plan on climate engineering is unclear. What is clear is that an open and constructive conversation on geoengineering has not yet begun in Australia.

2.5 Synthesis

Geoengineering is an emerging and contested issue in climate policy. Its history is intermingled with heroic ideas of weather modification designed to ease pressures in stressful times of drought, and its science is inseparable from that of climate processes and climate change. Although the use of geoengineering remains largely theoretical at this stage, there is a growing academic scholarship on whether it can be morally justified and if so, how it could be managed. Depending on how it is governed, geoengineering could pose either a threat or an opportunity for sustainability. For sustainable governance of geoengineering, research is needed into how proposed methods might affect ecosystems and society over the short-, medium- and long-term, what visions exist of a sustainable geoengineering future, and what science, policies, tools and skills are needed to steer proposals along sustainable trajectories. In this, scenarios can help to engage different parts of societies in difficult conversations about what geoengineering means, whether there is an acceptable place for it in the future, and what the likely trade-offs might be. Such conversations have not yet taken place in Australia. The ultimate aim of this thesis project is to determine whether and how a scenario exercise could usefully inform sustainable governance in Australia.

Chapter 3 – Geoengineering governance-by-default: an earth system governance perspective

3.1 The place of Chapter 3 in the thesis

Chapter 3 addresses Research Question 1 by reviewing the global geoengineering governance landscape using the ESG analytical framework.

RQ#1: Is global geoengineering governance currently on a trajectory towards sustainable outcomes?

(1) What existing governance instruments are relevant to geoengineering?

(2) Who are the principal actors currently engaged in geoengineering?

(3) What are the features and likely outcomes of geoengineering governance?

To understand how geoengineering is currently governed at the global level from a sustainability perspective, the ESG framework is used. It allows the governance landscape to be mapped according to both the formal 'architecture'—international treaties—and, where this is lacking, to the behaviour of key actors. These two features of governance—architecture and actors—are key because they allow scrutiny of engrained or emerging norms, which is a cross-cutting theme of the ESG framework. Norms can be detected both in treaties—legal norms—and in actors' behaviours—social norms—and can be indicative of the trajectory that geoengineering governance is tracking. In Chapter 3, these norms are identified through a qualitative evaluation of the governance landscape by means of a survey of regulatory instruments and of activities relevant to geoengineering. Characterisation of the norms that define the geoengineering governance landscape provides a way to explore the implications of continuing along the existing trajectory, and to identify what further research is needed if this trajectory is to be altered.

3.3 The significance of Chapter 3 to the thesis

The characterisation of geoengineering global governance as a form of governance-by-default makes two important contributions to the thesis. First, it recognises that existing geoengineering governance is not tracking on a sustainable trajectory. This is because governance-by-default fails to meet key criteria of sustainable governance. As there is no overarching strategy associated with it, it does not suggest a systemic approach to governance that appreciates the interlinked natures of various legal, social, cultural, technological and environmental systems. It is not forward-looking. State actors and regulators are described as adopting a 'watching brief' rather than scanning the future to understand how geoengineering may affect sustainability outcomes at a global or national level. It is not participatory. Governance-by-default allows the most active or vocal stakeholders in the geoengineering debate to set the agenda and potentially also the trajectory. These stakeholders can choose to adopt inclusive and participatory approaches in setting the agenda, but a power differential will likely remain.

The second contribution of Chapter 3 to the thesis is that it identifies the key norm-setting actors as epistemic communities (and particular those from Western industrialised countries in the Northern Hemisphere), which justifies the next stage of this thesis. Given the important role of researchers and scholars in geoengineering's governance-by-default, it is relevant to identify how these actors portray the future of geoengineering governance, what challenges they identify, and what options are proposed to steer geoengineering in a preferred direction.

Chapter 4 – Geoengineering governance challenges, priorities, and proposals

4.1 The place of Chapter 4 in the thesis

Chapter 4 is a manuscript submitted to the journal *Geoforum.* It addresses Research Question 2 by reviewing published geoengineering governance proposals.

RQ#2: Are proposed geoengineering governance designs in line with a sustainability agenda?

Chapter 3 established that global geoengineering governance is not being driven expressly by considerations of sustainability. In particular, existing arrangements do not suggest an overarching strategy that is forward-looking and inclusive in its visions of the future. Instead, a governance-by-default paradigm exists that is driven primarily by engaged individuals from academic and broader research communities. These actors may have a disproportionately influential effect on how governance might be considered and what options might be contemplated. Therefore, to understand what governance mechanisms and designs these actors are recommending, Chapter 4 reviews the geoengineering governance literature.

In Chapter 4, peer-reviewed and grey literature on geoengineering governance are analysed thematically to identify, first, what the authors judged as the key governance challenges of geoengineering, and, second, what solutions or governance design characteristics were proposed to address these challenges.

4.3 The significance of Chapter 4 to the thesis

The objective of Chapter 4 was to take stock of governance designs proposed for geoengineering and to understand whether sustainability is embedded within these. The analysis found that consensus on certain elements of geoengineering governance is building. The need for legitimacy through public engagement on geoengineering issues and clear communication about research, activities, and decision-making is a point of agreement across the literature. Another common feature is that all geoengineering proposals suggest the need ultimately for some form of treaty-based regulation. However, there is debate around how soon such regulation should be developed and what steps should be taken from now to assist in the design of that regulation. There are also other important points of difference that centre around the predispositions of individual stakeholders. Authors that prioritise governance concerns that relate to issues of global environmental governance issues tend to support a harm minimisation approach within existing multilateral environmental agreements, whereas authors that focus on the novel nature of geoengineering technologies emphasise the importance of supporting and protecting the knowledge creation process through regulation.

From this analysis Chapter 4 makes two key contributions to the thesis. First, it highlights that although some crucial elements of sustainability are well embedded within the debate and have gained acceptance, some others have not. Many do not take a holistic view of research and deployment that appreciates the relevance of early research decisions to shaping governance. Very few proposals highlight the importance of building visioning exercises—that are both exploratory and participatory—into the governance design process.

Second, it suggests that neither the challenges of geoengineering governance nor the proposed ‘solutions’ are new. Whereas the mere mention of geoengineering was once considered taboo, we are now at risk of normalising the debate to such an extent that major risks and novel opportunities are obscured. What is missing is a strong emphasis on the future and on understanding what is expected of geoengineering; does geoengineering fit within a sustainable outlook?

In line with the central objective of this thesis—which is to investigate whether and how a scenario exercise might inform Australian geoengineering policy development—these two contributions justify further exploration of the use of foresight tools, specifically scenarios, in policy-relevant geoengineering research.

Chapter 5 – How geoengineering scenarios frame assumptions and create expectations

5.1 The place of Chapter 5 in the thesis

Chapter 5 addresses Research Question 3 by reviewing geoengineering scenarios from the literature to identify emerging expectations and assess these in the context of sustainability science.

RQ#3: How do academics envision geoengineering?

1. *How are scenarios used in geoengineering research?*
2. *What are the key characteristics of geoengineering scenarios?*
3. *What assumptions and expectations do they suggest?*
4. *What are the sustainability science implications?*

Chapter 3 established that geoengineering is not purposefully governed but that the academic community, as the most active stakeholders in the debate, have a strong influence on how geoengineering may ultimately be governed. From this, two questions arise: first, what governance arrangements do scholars propose; and second, what do scholars expect or assume as the characteristics or roles of geoengineering? Chapter 4 explored the former. Chapter 5 explores the latter.

Chapter 5 identifies common features and characteristics, prevailing practices, and key assumptions or omissions within geoengineering scenarios as a way to identify emerging expectations. It then considers these defining qualities in the context of sustainability science.

Supplementary material referred to in Chapter 5 is included as Appendix A.

5.3 The significance of Chapter 5 to the thesis

The question addressed in this chapter is how academics—who are instrumental in shaping geoengineering governance—envision geoengineering. This was studied by focussing on the use of scenarios and common features across them. The analysis found that geoengineering scenarios are used heavily in the physical sciences, particularly for climate modelling, as a way to build scientific knowledge. However, scenarios are also increasingly used in the social or mixed sciences in one of two ways: as a way to frame a discussion about certain potential implications of deploying or not deploying geoengineering; and a way to explore potential futures.

Computer modelling scenarios for scientific knowledge-building dominate and therefore merit attention. These scenarios focus on standard mean metrics such as temperature and rainfall (other metrics are rarely studied) and assume that geoengineering aims to maintain a climate *status-quo.* To achieve this, SRM is treated as a non-disruptive off-the-shelf product in which geoengineering is isolatable from other environmental and social systems that are unchanged throughout the scenario.

Although this is often necessary for scientific purposes, from a sustainability science perspective, this is problematic for a number of reasons. The homogeneity of scenarios, which is intended to reduce scientific uncertainty, misrepresents the range of possible futures and may lead to key factors being tested within a limited range. Less common events, whether natural or anthropogenic, are not studied, meaning that surprises are likely in the future. The focus on global effects resulting from global actions is to the detriment of understanding local or regional effects and actions. The techno-optimistic premise of the scenarios ignores the interconnectedness of nature and society and diverts attention from alternative or complementary actions. This all serves to create path dependencies and close down the options available to policymakers.

The social science scenarios are less harmonised, but nonetheless reveal some tendencies. Many rely heavily on a ‘last resort’ framing of geoengineering to build arguments around the need for research. These scenarios position geoengineering deployment as a problem of the future and deflect attention from the implications of geoengineering research. This can alienate interested stakeholders, such as local communities, who may want to engage in the issues now. Further to this point, interdisciplinarity is not a widespread in this literature. Only the exploratory scenarios, those that seek to discover potential futures, apply inclusive and participatory scenario construction processes.

Chapter 5 hypothesises that the shape of scenarios has an effect on what is expected and desired from geoengineering, and currently these scenarios do not portray a broad range of views and options. Local and broadly scoped scenarios that incorporate many societal views are not widespread. Ultimately, the way geoengineering is envisioned in not sustainable. This conclusion leads naturally to, and informs, the central question of this thesis, which asks how a scenario exercise can inform geoengineering policy development in line with concepts of sustainability.

This Chapter 5 paper was featured in a commentary article in Issue 5 of the first volume of *Nature Sustainability* in the News & Views section (Knutti, 2018). Reflecting on the paper, Knutti (2018) notes that although the dominance of climate-modelling scenarios in the geoengineering scenarios literature, and the expectations that these generate, do not represent concerted attempts to influence policymakers, climate scientists should consider how ‘findings and framings can inadvertently distort the perceived likelihood of future events and how readers interpret such probabilities’ (p. 215). Knutti (2018) points to criticisms of modelers for ‘tweaking their models’ (p. 214) so that, for example, plausible CDR efforts are deemed sufficient to meet targets outlined under the Paris Agreement. That the article, and these insightful comments, were authored by prominent climate modeller Professor Reto Knutti serves to underscore the significance of the findings in Chapter 5 and the important contribution of Talberg et al. (2018b).

Chapter 6 – A scenario process to inform Australian geoengineering policy

6.1 The place of Chapter 6 in the thesis

Chapters 6 and 7 address the central research question by developing scenarios and analysing:

RQ#4: How can a scenario exercise inform sustainable geoengineering governance in Australia?

Chapter 5 established that scenarios are important not just for learning about geoengineering but also for setting governance trajectories. Chapter 6 therefore presents the design of a scenario exercise in Australia as a means to test whether a scenario exercise can inform geoengineering policy development.

The design of the scenario process in Chapter 6 is informed by the findings in Chapter 5; that geoengineering scenarios, in the context of sustainability science, should incorporate participatory and inclusive processes, should have a broad scope on climate policy rather than exclusively on geoengineering or SRM, and should narrow the focus to issues more local than just the global.

To begin to answer the central thesis question, Chapter 6 goes beyond merely creating scenarios and also analyses the scenarios. Chapter 5 scrutinised geoengineering scenarios in three categories with a strong focus on the computer modelling scenarios because these dominated. However, Chapter 5 also scrutinised the few exploratory scenarios that existed in the literature and found that a number of key determinants of a geoengineered future emerged from the perspectives of the participants. In Chapter 6, to validate the proposed method, the ideas are compared to the determinants from Chapter 5. Next, the analysis seeks insights directly from the scenario content. Finally, the analysis tracks the evolution of shared learning across the scenario-construction process as a way to underscore the value of such processes.

Full narratives of the scenarios developed in Chapter 6 are included as Appendix B.

6.3 The significance of Chapter 6 to the thesis

Chapter 6 asked whether a scenario method can be used to contribute to a ‘sustainable’ policy process and suggests that it can. Through the process and scenarios developed in Chapter 6, it was found that viable and effective policy options for Australia may be to engage with the issue of geoengineering, both nationally and internationally, and to do so with the expectation that temperatures will exceed two degrees before the end of the century, bringing with them serious climate impacts.

Findings from Chapter 6 suggest that policymakers would be wise to be perceptive to how the geoengineering debate progresses and whether technologies are framed as climate mitigation, adaptation, or optimisation. This framing may differ in Australia from other parts of the world, and governments may play either active or passive roles in this framing.

Important contributions of Chapter 6 are in starting a conversation on geoengineering in Australia and, in doing so, starting to fill a gap in the geoengineering scenarios literature; in understanding some of the Australia-specific considerations of geoengineering; and in opening up the scope of viable policy options.

Chapter 7 – Stress-testing Australian climate policy using geoengineering scenarios

7.1 The place of Chapter 7 in the thesis

Chapters 6 and 7 address the central research question by developing scenarios and analysing:

RQ#4: How can a scenario exercise inform sustainable geoengineering governance in Australia?

Chapter 7 builds on Chapter 6 by adding a second layer of analysis to the scenarios. It is based on a manuscript currently under review at the journal *Technological Forecasting and Social Change*. Whereas the scenario analysis in Chapter 6 sought to identify relationships and pre-determined elements from the scenarios themselves, Chapter 7 proposes and then illustrates a method to test proposed government policies.

7.3 The significance of Chapter 7 to the thesis

Chapter 7 is a second element to addressing the question on whether a scenario method can be used effectively to contribute to a 'sustainable' policy process. The chapter distinguishes between different ways to analyse scenarios. Whereas Chapter 6 created four geoengineering scenarios and used them to 'see' new insights (understood as being in the 'generative mode'), Chapter 7 focuses on 'seeding' the future (the 'adaptive mode'), in that it explores the ways in which scenarios can be used to stress-test Australian climate policy strategies.

The chapter highlights how scenarios can successfully draw out implicit assumptions underpinning policy strategies, making them transparent and therefore modifiable. It also demonstrates how scenarios can assist in scrutinising or designing policy settings such that they can be made robust to a range of futures.

As Australia has no explicit position on geoengineering, the analysis in Chapter 7 assesses Australian climate mitigation and adaptation strategies only. Australia's National Climate Resilience and Adaptation Strategy document forms the basis of the analysis on the adaptation side. In the absence of a 2050 emissions reduction strategy, the CCA's 'Special Review on Australia's Climate Goals and Policies' forms the basis for the analysis on the mitigation side. Findings from Chapter 7 suggest that these policy documents do not outline strategies that are highly robust to different potential 2050 global scenarios. Instead, they are premised on the expectation that governments will always have legitimacy and influence, and that solutions to 'wicked problems' will come in the form of technology rather than behavioural change, or a combination of both (Grubler et al., 2018). The analysis also illustrates that Australia's engagement with geoengineering is currently following a trajectory that closely resembles one of the four scenarios. This suggests that there may be value in better understanding the characteristics, risks, and opportunities of that scenario, as well as possible turning points within it.

A key contribution of Chapter 7 is in proposing a climate strategy for Australia that includes investing in decarbonisation of the economy; preparing for impacts of climate change in line with the highest range of warming projections; starting a technologically and ideologically neutral conversation on CDR and SRM with all sectors of Australian society; financing an interdisciplinary, transparent and inclusive research program on the implications of, and capacity for, geoengineering in Australia; and engaging actively in geoengineering discussions internationally.

Chapter 8: Conclusions

This final chapter collates outcomes from the research and the thesis' key contributions. The relevance of these findings and their bearing on how geoengineering could be governed is further clarified by highlighting the main limitations and challenges of the study. Although the thesis makes a series of contributions to the literature and advances knowledge in field, it inevitably also poses many more questions. Therefore, this chapter also provides suggestions of directions for further research and how these might build on, challenge, or strengthen, the findings from this study.

8.1 Main findings

The thesis studied how the use of scenarios can play a role in the design of geoengineering governance. The context for the research was climate policy in Australia, as viewed through a sustainability science lens. The thesis contributes to understanding of what is shaping geoengineering governance and how the judicious and considered use of scenarios can inform the design of sustainable governance. Within the boundaries set by the central aim of the thesis, individual research questions evolved over the course of the study, guided by the findings from the various stages of the study. By adopting an incremental interdisciplinary mixed-methods approach that reflects a pragmatist perspective the thesis also contributes to the advancement of futures studies by demonstrating a way of using exploratory scenarios in a contested public policy context.

Key findings are presented for each research question.

8.1.1 Research question #1

Is global geoengineering governance currently on a trajectory towards sustainable outcomes?

(1) What existing governance instruments are relevant to geoengineering?

(2) Who are the principal actors currently engaged in geoengineering?

(3) What are the features and likely outcomes of geoengineering governance?

Before delving into the future, the research began by exploring the present and thus seeking to understand how geoengineering governance has evolved to date, with a focus on determining the direction in which any existing momentum might be heading. Although a substantial volume of existing research examines the extent to which, and how, existing international treaties already govern geoengineering, there has not been a focus on the development of norms through the application of these treaties or through the actions of key players. This gap is addressed in Research Question 1 through the analytical framework of ESG as a way to draw out whether global geoengineering governance is on a trajectory towards sustainability.

Outcome 1: The study found that global geoengineering governance can be characterised as a form of *governance-by-default*. There is no purposive regulation. Decisions that affect geoengineering research or deployment are made in line with existing norms and are driven by the motivations of those actors most active in the debate. This occurs due to weak opposition from other stakeholders (such as regulators) who are content to adopt a 'wait and see' approach.

Outcome 2: The study identifies the key norm-setting actors as research communities, especially from Western industrialised Northern Hemisphere countries. In a situation of governance-by-default, the agenda is set by the most engaged players in the debate. As a result, the study found that scientists and scholars have begun defining rules on geoengineering research through self-regulation and that they influence the shape of broader governance by advocating certain terms of deployment.

Outcome 3: From Outcomes 1 and 2, it is clear that existing geoengineering governance is not tracking a sustainable trajectory. By lacking an overarching strategy, this form of governance does not consider the interconnected nature of Earth/human systems, and fails to adopt an anticipatory approach, both of which are central to sustainable governance. Further, the key norm-setting actors do not represent an inclusive or balanced range of views relevant to geoengineering decision-making.

8.1.2 Research question #2

Are proposed geoengineering governance designs in line with a sustainability agenda?

Research Question 2 was motivated by the findings from Research Question 1. The principal actors engaged in geoengineering were found to be scientists and scholars, and by the nature of governance-by-default these actors have substantial influence over the shape of geoengineering governance that might develop. It therefore becomes relevant to understand how these actors comprehend the future of geoengineering governance, what they identify as the key challenges, and what options they propose for managing geoengineering. The academic and grey literature on geoengineering policy proposals has grown in recent times, but little attention has been paid to whether this literature is evolving productively and producing advances in geoengineering governance thinking. This gap is addressed through a stocktake of ideas on geoengineering governance, specifically a thematic review of the relevant literature. The study views the body of literature through a sustainability science lens and asks whether proposed geoengineering governance designs align with a sustainability agenda.

Outcome 1: Authors of governance proposals converge on the need for legitimacy in geoengineering governance through transparent and inclusive engagement on geoengineering issues, but also on the need for open and clear communication about research, activities, and decision-making.

Outcome 2: There is also convergence on the need for treaty-based regulation, but authors disagree on the urgency of this and what should inform its design.

Outcome 3: Neither the challenges of geoengineering governance, nor the proposed 'solutions' are treated as novel. The challenges can be categorised as issues of global environmental governance or those of emerging technologies, or they can be likened to existing issues in other policy domains. Which challenges are prioritised and what policy 'solutions' are proposed depend on the disciplinary disposition of the analyst. It is possible that the geoengineering debate has been normalised to such an extent that major risks and novel opportunities are not being detected.

Outcome 4: Proposed geoengineering governance designs go some way towards a sustainability agenda but lack key elements. Despite a convergence on legitimacy, transparency, and inclusiveness, all of which are relevant to sustainable governance, other crucial elements are missing or under-emphasised. In particular, a substantial portion of the literature fails to appreciate the influence of research decisions on shaping governance.

Outcome 5: Although there is evidence of a growing interest in concepts of responsible innovation, only a limited number of governance proposals stresses the importance of anticipatory processes such as exploratory and participatory visioning exercises.

8.1.3 Research question #3

How do academics envision geoengineering?

1. *How are scenarios used in geoengineering research?*
2. *What are the key characteristics of geoengineering scenarios?*
3. *What assumptions and expectations do they suggest?*
4. *What are the sustainability science implications?*

Research Question 3 was motivated by findings from Research Questions 1 and 2. As academics were found to fill a key function in shaping geoengineering governance, it is relevant to understand how these players envisage that geoengineering will exist in the future. Chapter 4 found that the geoengineering governance literature often fails to appreciate the influence of research decisions on shaping governance. It is therefore relevant to examine geoengineering scenarios in a way that extricates the key characteristics of geoengineering scenarios, plus the assumptions and expectations that inspire them, and then assess these for their adherence to principles of sustainability science.

Outcome 1: The analysis found that geoengineering scenarios are used in three distinct ways, but predominantly in the physical sciences to build scientific knowledge, especially in climate modelling. The second and third uses are in the social or mixed sciences either as a way to frame discussions on the implications of geoengineering deployment or to explore geoengineering futures.

Outcome 2: Computer modelling geoengineering scenarios are relatively harmonised. To the exclusion of other metrics, they focus on standard metrics such as mean temperature and rainfall, and analyses assume that geoengineering serves to maintain a climate *status-quo.* This approach reduces scientific uncertainty, but misrepresents the range of possible futures, which may lead to key factors being tested within a limited range or certain potential problems being over-emphasised and may increase vulnerability to other ‘surprise’ events. SRM is included as a ‘plug-and-play’ solution to climate change that is isolatable from other environmental and social systems.

Outcome 3: Many of the scenarios used in social sciences rely on a ‘last resort’ framing of geoengineering to build arguments around the need for research. Geoengineering deployment is thus presented as a future problem. This can alienate interested stakeholders that may want to engage in the issues now and can deflect attention from the implications of geoengineering research.

Outcome 4: From Outcomes 1 to 3, it is suggested that the way geoengineering is envisioned in scenarios is not in line with concepts of sustainability. A focus in the scenarios on global effects resulting from global actions results in a gap around understanding local or regional effects and actions. Scenarios do not portray a broad range of perspective, worldviews, interests and concerns as interdisciplinarity is not prevalent in this literature. The techno-optimistic premise of most of the scenarios, especially the computer modelling scenarios, ignores the interconnectedness of nature and society and obscures alternative or complementary actions, thus potentially closing down the options available to policymakers.

8.1.4 Research question #4

How can a scenario exercise inform sustainable geoengineering governance in Australia?

Research Question 4 stemmed from the findings of Research Questions 2 and 3. Analysis of governance proposals suggested that the geoengineering debate may be overly focussed on applying pre-existing policy solutions to the challenges of geoengineering, deemed not to be novel. As a result, there is little attention paid to low-probability events and potentially unique outcomes. Analysis of the geoengineering scenarios resulted in similar conclusions, finding that scenarios tend not to reflect a broad range of views and therefore tend not to be highly diverse, yet may have an impact on how geoengineering is understood and what is expected of the technologies. Generally, a sustainability agenda is not a key component of governance proposals, nor of geoengineering scenarios. Local and broadly-scoped scenarios incorporating diverse societal views are not widespread. These findings justify a focus on designing scenarios that reflect an interdisciplinary and inclusive approach as a means to inform sustainable geoengineering governance. Research Question 4 therefore asks how this can be done.

To address this question, a scenario construction method was proposed drawing on and remedying the failings of, or gaps in, geoengineering scenarios identified in response to Research Question 3. The scenarios that result from this method are assessed and analysed in several ways. The fundamental elements of the scenarios are compared to the key determinants of scenarios identified in the geoengineering scenarios literature. The scenarios are then scrutinised individually and as a family to identify causal relationships and pre-determined elements that may provide early warning signals of impending futures. The evolution of shared learning across the scenario-construction process is also explored as a way to underscore the value of, and validate, the process. Finally, current or proposed government policies are stress-tested against the scenarios to highlight implicit assumptions and therefore potential weaknesses in the policies and to inform a robust strategy.

Outcome 1: The analysis finds that the Australian government does not have a climate strategy that is robust to different potential 2050 global scenarios. Current or proposed policies are founded on the expectation that trust in government is steady into the future and that technological solutions are likely to obviate the need for behavioural change.

Outcome 2: Analysis suggests that a viable and effective strategy for Australia may be to engage with the issue of geoengineering, both nationally and internationally, including by beginning a technologically and ideologically neutral conversation with a broad audience, and by investing in transparent and inclusive research on the implications of geoengineering.

Outcome 3: At the same time as engaging with the issue of geoengineering, the analysis suggests that a robust climate strategy for Australia is to prioritise decarbonisation of the economy and to prepare for impacts of climate change in line with warming in excess of 2°C before the end of the century.

Outcome 4: Geoengineering could be framed as a form of climate mitigation, adaptation, or optimisation. This framing may differ in Australia from elsewhere and may result from either active or passive government involvement, but it could influence how geoengineering is implemented and what sustainability threats or opportunities arise. The current trajectory of Australia's engagement with geoengineering aligns closely with a scenario in which geoengineering is framed as a form of adaptation. There may be value in better understanding the characteristics, risks, and opportunities of that scenario.

Outcome 5: Outcomes 1 to 4 suggest that a carefully designed scenario process can produce scenarios that successfully inform sustainable geoengineering governance by drawing out implicit assumptions underlying decision-making and by testing the strength of a range of policy options. The process can also instigate shared learning of a complex issue and promote structured but impartial discussion across a broad spectrum of stakeholders.

8.2 Challenges and limitations

The research upon which this thesis is based presented a series of challenges. Actions taken, or decisions made, to overcome these challenges have, in some instances, limited the applicability or relevance of some of the findings. These challenges and resulting limitations to the relevance of the research are noted here.

8.2.1 Definitions and search strings

Geoengineering is a broad and mixed collection of technologies, and as such, invokes a plethora of concerns and potential research directions. The decision was made early in the research process not to focus on any individual technology or technology-type but to engage with the broad concept of geoengineering. This presented a key limitation relating to the ambiguous definition of geoengineering and determining the scope of literature to consider. Questions are raised for example around whether standalone-CCS should be included, or whether afforestation is considered a form of geoengineering.

To avoid delving deep into these issues, literature searches were restricted to the terms 'geoengineering' and 'climate engineering'. Individual technologies were not listed in search strings, meaning that the coverage was not comprehensive in this regard (for example in Chapters 4 and 5). Thus, the findings are relevant only insomuch as the authors of relevant papers choose to engage with the specific geoengineering literature by listing geoengineering in the keywords or abstracts, for example.

Similarly, in Chapter 5, the term 'scenarios' was used to identify relevant literature. Synonyms such as 'pathways', 'projections', 'forecasts', or 'visions' were not included in the search string. This decision was made to avoid including too many dissimilar and potentially incomparable products. However, an analysis on the sensitivity of the findings to the search string may help to contextualise the findings. Including Integrated Assessment Models or game theoretic simulations may add insight, for example.

8.2.2 Analytical framework

A limitation of Chapter 3 is that only one, rather than all four, of the cross-cutting themes of the ESG framework is explored. Although not studied, 'power', 'knowledge', and 'scale' would have each likely shed light on where geoengineering might be headed. This is especially true because geoengineering is characterised by a high level of complexity and scientific uncertainty, which means that a knowledge imbalance can create a power imbalance; experts from countries with more established scientific capabilities might be able to distance and even alienate from the discussion those without specific expertise or the resources to develop it (Karlsson et al., 2007). The focus on norms was adopted at the outset as a tangible and highly relevant aspect to explore in the context of there being no purposive governance for geoengineering. However, analysis of the three other cross-cutting themes is likely to have provided additional insight. Another limitation of the approach is that the governance landscape explored through ‘architecture’ and ‘actors’ is dynamic and ever-changing. Already new and relevant advances have been witnessed which may or may not alter the conclusions if included in the analysis.

8.2.3 Practical realities of scenarios

The practical application of scenarios presents limitations. The process and value of exploratory and participatory scenarios are not well understood in Australia. Few of those contacted to participate in the scenario exercise had much, if any, experience with the development of scenarios. As a result, active engagement in the process was not immediate; it grew over the course of the project. According to anecdotal feedback, it was not until several weeks later that the full value of the activity was realised by many of the participants. Yet, the success of any such exercise is crucially tied to the level of engagement and commitment of the participants. Thus, the scenario process may have provided additional insight had the participants better understood and been more aware of the activity’s significance and demands. As familiarity with participatory scenario processes grows, these are likely to be more successful and effective (Volkery et al., 2008).

Linked to this, is the inherent time requirement of participatory approaches (Richards et al., 2004). Inevitably, compromises must be made between on the one hand allowing sufficient time to deliberate, discuss, and learn throughout the process, and on the other hand attracting expert participants, who often have competing demands on their time and therefore limited availability. Here, a one-day workshop was determined as an adequate compromise, whereas a two-day workshop may have yielded more insightful contributions (but is unlikely to have attracted the same calibre of participants).

8.2.4 Thesis by publication

Finally, the format of the thesis, as one delivered through a series of publications, has both advantages and limitations. The benefits are that ideas and methods can be tested with peers as the research progresses. In this thesis, the research was clarified and strengthened as the ideas were defended in the face of scientific scepticism. A number of weaknesses were identified in the analysis and addressed, thus increasing the value of the research and its contribution.

However, each time a paper was submitted for peer-review, it was subject to scrutiny from reviewers that could only consider the research in the narrow context of the paper, without knowledge of the overarching study. As a result, comments from reviewers, which were greatly appreciated, somewhat altered the course of the research through changes to the methods, for example. This was problematic because the long timeframes of the publication process did not align well with that of a time-limited PhD project. Decisions on research design in subsequent phases of the study were needed before comments had been received on precursory papers. Although the effect of this was ultimately minimal, it threatened to disrupt the coherence of the project in its totality.

8.3 Major contributions

The thesis makes key contributions to the fields of geoengineering governance, scenario-based research and Australian climate policy.

Contribution 1: The thesis establishes that geoengineering governance is not tracking on a sustainable trajectory globally. Current and proposed arrangements fail to consider and anticipate the potentially stochastic nature of Earth/human systems and are guided by the actions or interests of a limited group of stakeholders, specifically epistemic communities (and particular those from Western industrialised countries in the Northern Hemisphere). The findings prompt researchers to consider the implications of, and then justify, their research design decisions, for example in relation to scenarios.

Contribution 2: Methods for developing and analysing scenarios are proposed and demonstrated. The research reveals the central role that scenarios already play in geoengineering scholarship and governance design but demonstrates that this can be expanded. Important but underutilised functions of scenarios are highlighted as providing platforms for inclusive and impartial conversations on geoengineering, making transparent implicit assumptions underpinning decision-making, and allowing scrutiny of policy settings that are robust to a range of futures.

Contribution 3: The project begins an interdisciplinary and cross-sectoral conversation on geoengineering in Australia and makes Australia-specific policy recommendations. In doing so, it opens up the scope of viable policy options and fills a gap in the geoengineering literature.

8.4 Future research

As the research progressed, in particular as each chapter or paper was completed, multiple avenues of research were revealed. Although these were not pursued as part of the thesis, they present potentially fruitful directions for further research. In many ways, the identification of further research is a different perspective on the recognition of research limitations.

As previously noted, the analytical framework underpinning Chapter 3 explored just one of the four cross-cutting issues of the ESG framework. ‘Power’, ‘knowledge’, and ‘scale’ were not studied and yet present fertile grounds for further scholarship. Similarly, three of the ESG’s five interlinked dimensions—specifically ‘adaptiveness’, ‘accountability and legitimacy’, and ‘allocation and access’—were not assessed with regard to geoengineering governance. Doing so might bring to the fore implications of geoengineering for such things as meeting basic human needs, and the distribution of both risks and responsibilities.

Those dimensions that were explored suggested that geoengineering is being steered by a form of governance-by-default, which was defined as having:

> an absence of purposive regulation, an existing driver (here, the ‘2C&0Gt’ target as established by a norm of harm minimisation), a propensity for regulators to postpone decision-making (here, in anticipation of improved scientific certainty to resolve the tension between precaution and harm minimisation), engagement dominated by one actor-group (here, academia), and ultimately a blurring of the lines between the

> different roles of societal players (here, related to the difficulty in separating research from deployment) (Talberg et al., 2018a, p. 49).

This definition can be used to test whether other policy domains are subject to a similar management scheme. For example, in the area of ocean acidification it has been suggested that purposive environmental management has a narrow purview and has thus far had limited success (Billé et al., 2013). Is ocean acidification subject to a form of governance-by-default?

Chapter 4 was a thematic review of challenges and policy 'solutions' for geoengineering governance. It suggested that the disciplinary predisposition of protagonists tends to skew the types of geoengineering challenges and 'solutions' that are prioritised or proposed and that this may risk normalising the debate by ignoring potentially novel issues or ideas. Further scholarship in this area might seek to interrogate specific authors on their academic disciplines and to link previous research from these authors to their geoengineering governance scholarship. This might help to highlight any bias in the geoengineering governance scholarship and may instigate a broadening of the research agenda. Also, the suggestion that the geoengineering debate may become normalised sits in clear contrast to claims of exceptionalism in geoengineering scholarship (Heyward, 2015). Further research may seek to more clearly define these two ideas and then to determine the extent to which either may or may not be occurring and therefore influencing governance deliberations.

Chapter 5 was a meta-analysis of scenarios used in geoengineering research. The analysis rested on the premise that scenarios:

> play an important role in the development and propagation of shared visions of the future, creating powerful expectations of the economic, social and environmental potential of emerging technologies; and mobilising the intellectual, financial, political and institutional resources necessary for their realisation" (McDowall and Eames, 2006, p. 1236).

It thus sought to determine what characteristics and aspects of these scenarios dominate. A meta-analysis can uncover trends or deficiencies and can speculate as to the effect of these on expectations. However, to ascertain *why* certain features dominate (or not) and *how* or *to what extent* this influences expectations requires targeted interviews with researchers, the public, and decisionmakers. Such research would be highly relevant beyond geoengineering scholarship, especially in the field of climate research where there is a strong history of scenario use and '[c]limate governance is being increasingly organized around [these] pathways' (Beck and Mahony, 2017, p. 312).

Finally, and as noted in Chapters 6 and 7, although scenarios cannot provide definitive answers because the future has not yet occurred and therefore cannot be tangibly studied, they are useful tools for identifying paths of further research and for informing the design of such research. The scenario exercise undertaken in this project suggested that research needs to be conducted into understanding how geoengineering perceptions are evolving in Australia. Research questions of interest might include: Is geoengineering perceived and understood as a form of climate adaptation, mitigation or optimisation? Do perceptions vary across the population? For example, are the views of scientists or their funders at odds with those of Australian societies? Is there a greater public acceptance of geoengineering as it relates to the oceans? If so, why, and is this reflected elsewhere in the world? Some of this research could be undertaken through participatory geoengineering backcasting processes as a means to understand what a desirable future resembles and whether a sustainable trajectory towards such a future exists.

8.5 Concluding remarks

The aim of the research was to progress understanding on whether and how scenarios might be used to inform sustainable geoengineering policy in Australia. The study highlighted the lack of a sustainability agenda in current geoengineering governance foci and in relevant scholarship. Participatory and exploratory scenarios are ways to incorporate sustainability values and practice into the design of governance mechanisms. Australia’s approach to climate policy has to date been dogmatic and short-sighted. The use of geoengineering scenarios can break this tradition. Here, it has revealed that Australian climate policy needs to be broadened to include a debate on geoengineering.

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Note: includes all references for all chapters, including those from published papers.

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Appendix A – Supplementary Material for Chapter 5

Table A.1: Review database including author(s), year and journal or research institution for 102 papers using scenarios to analyse geoengineering.

Author(s)/year	Journal or institution
Alterskjær et al., 2013	*Journal of Geophysical Research: Atmospheres*
Amelung & Funke, 2014	*Human and Ecological Risk Assessment: An International Journal*
Ammann, Washington, Meehl, Buja, & Teng, 2010	*Journal of Geophysical Research-Atmospheres*
Applegate & Keller, 2015	*Environmental Research Letters*
Aswathy et al., 2014	*Atmospheric Chemistry and Physics Discussions*
Bala & Nag, 2012	*Climate Dynamics*
Banerjee, Collins, Low, & Blackstock, 2013	Yale Climate and Energy Institute and Centre for International Governance Innovation
Bates, 2012	*Climate Dynamics*
Baum, Maher, & Haqq-Misra, 2013	*Environment Systems & Decisions*
Bellamy & Healey, 2015	Institute for Science Innovation and Society, Oxford
Berdahl et al., 2014	*Journal of Geophysical Research: Atmospheres*
Bickel, 2013	*Environment Systems & Decisions*
Bickel & Agrawal, 2013	*Climatic Change*
Bodansky, 2013	*Climatic Change*
Böttcher, Gabriel, & Harnisch, 2015	Priority Programme 1689 of the German Research Foundation DFG
Böttcher, Gabriel, & Low, 2016	Institute for Advanced Sustainability Studies
Boucher et al., 2012	*Environmental Research Letters*
Bouttes, Gregory, & Lowe, 2013	*Journal of Climate*
Brovkin et al., 2009	*Climatic Change*
Bürger & Cubasch, 2015	*Journal of Geophysical Research: Atmospheres*
Caldeira & Wood, 2008	*Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*
Cao & Caldeira, 2010	*Environmental Research Letters*
CBD Secretariat, 2012	Convention on Biological Diversity, Technical Series
Chen & Yin, 2014	*Journal of Geophysical Research: Atmospheres*
Couce, Irvine, Gregoire, Ridgwell, & Hendy, 2013	*Geophysical Research Letters*
de Larragan, 2012	*Climate Policy*
Denman, 2008	*Marine Ecology Progress Series*
Doda, 2014	Grantham Research Institute on Climate Change and the Environment
Eliseev, 2012	*Atmospheric and Oceanic Optics*
Eliseev, Chernokulsky, Karpenko, & Mokhov, 2010	*Theoretical and Applied Climatology*
Eliseev & Mokhov, 2009	*Izvestiya Atmospheric and Oceanic Physics*
Gabriel & Robock, 2015	*Atmospheric Chemistry and Physics Discussions*
Goes, Tuana, & Keller, 2011	*Climatic Change*
Grandey & Wang, 2015	*Scientific Reports*

Haraguchi et al., 2015	Global Governance Futures
House of Commons Science and Technology Committee, 2010	UK Parliament
Horton, 2011	*Stanford Journal of Law, Science and Policy*
Irvine, Sriver, & Keller, 2012	*Nature Climate Change*
Izrael, Volodin, Kostrykin, Revokatova, & Ryaboshapko, 2013	*Russian Meteorology and Hydrology*
Jackson et al., 2015	*Geophysical Research Letters*
Jarvis & Leedal, 2012	*Atmospheric Science Letters*
Jones, Haywood, & Jones, 2016	*Atmospheric Chemistry and Physics Discussions*
Jones, Haywood, Boucher, Kravitz, & Robock, 2010	*Atmospheric Chemistry and Physics*
Keith & MacMartin, 2015	*Nature Climate Change*
Keller, Feng, & Oschlies, 2014	*Nature Communications*
Korhonen, Carslaw, & Romakkaniemi, 2010	*Atmospheric Chemistry and Physics*
Kravitz et al., 2011	*Journal of Geophysical Research: Atmospheres*
Kravitz et al., 2013	*Atmospheric Science Letters*
Kwiatkowski, Cox, Halloran, Mumby, & Wiltshire, 2015	*Nature Climate Change*
Laakso et al., 2016	*Atmospheric Chemistry and Physics*
Laakso et al., 2012	*Environmental Research Letters*
Lempert & Prosnitz, 2011	RAND Corporation
Llanillo, Jones, & von Glasow, 2010	*Atmosphere*
MacMartin, Caldeira, & Keith, 2014	*Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*
Manfready, 2011	*International Journal of Environmental Sciences*
Matthews & Caldeira, 2007	*Proceedings of the National Academy of Sciences*
McCusker, Armour, Bitz, & Battisti, 2014	*Environmental Research Letters*
McInnes, 2010	*Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*
Milkoreit, Low, Escarraman, & Blackstock, 2011	Canada Europe American Dialogue on Security
Moore et al., 2010	*Proceedings of the National Academy of Sciences*
Moore et al., 2014	*Proceedings of the National Academy of Sciences*
Moore et al., 2015	*Journal of Geophysical Research: Atmospheres*
Muri, Niemeier, & Kristjánsson, 2015	*Geophysical Research Letters*
Naik, Wuebbles, DeLucia, & Foley, 2003	*Environmental Management*
NAS, 2015	National Academy of Science
Niemeier, Schmidt, Alterskjaer, & Kristjánsson, 2013	*Journal of Geophysical Research: Atmospheres*
Niemeier, Schmidt, & Timmreck, 2011	*Atmospheric Science Letters*
Olson, 2011	Woodrow Wilson International Center for Scholars
Parkes, Gadian, & Latham, 2012	*ISRN Geophysics*
Parson, 2014	*Transnational Environmental Law*
Partanen et al., 2013	*Atmospheric Chemistry and Physics*

Princiotta & Loughlin, 2014	*Journal of the Air & Waste Management Association*
Pringle et al., 2012	*Atmospheric Chemistry and Physics*
Rasch, Tilmes, et al., 2008	*Geophysical Research Letters*
Rasch, Crutzen, & Coleman, 2008	*Environmental Research Letters*
Rasch, Latham, & Chen, 2009	*Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*
Ricke, Morgan, & Allen, 2010	*Nature Geoscience*
Ricke, Morgan, Apt, Victor, & Steinbruner, 2008	Council of Foreign Relations.
Rickels, Rehdanz, & Oschlies, 2009	*Resource and Energy Economics*
Robock, 2014	*Book chapter in Geoengineering of the Climate System*
Robock, Oman, & Stenchikov, 2008	*Journal of Geophysical Research: Atmospheres*
Schaller, Sedláček, & Knutti, 2014	*Journal of Geophysical Research: Atmospheres*
Schmidt et al., 2012	*Earth System Dynamics*
Schwartz & Randall, 2003	Pentagon
Smith & Rasch, 2013	*Climatic Change*
STUDY SPONSORED BY BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE, n.d.	National Academy of Science
Svoboda, 2012a	*Ethics & the Environment*
Svoboda, 2012b	*Journal of Applied Philosophy*
Svoboda, 2015	*Environmental Ethics*
Sweeney, 2014	*Futures*
Thomas et al., 2011	*Atmospheric Chemistry and Physics*
Tilmes, Garcia, Kinnison, Gettelman, & Rasch, 2009	*Journal of Geophysical Research-Atmospheres*
Tilmes, Jahn, Kay, Holland, & Lamarque, 2014	*Geophysical Research Letters*
Tjiputra, Grini, & Lee, 2016	*Journal of Geophysical Research: Biogeosciences*
Vaughan & Lenton, 2012	*Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*
Volodin, Kostrykin, & Ryaboshapko, 2011a	*Atmospheric Science Letters*
Volodin, Kostrykin, & Ryaboshapko, 2011b	*Izvestiya Atmospheric and Oceanic Physics*
Wigley, 2006	*Science*
Wilhelm, Davin, & Seneviratne, 2015	*Journal of Geophysical Research: Atmospheres*
Wu, Ridley, Pardaens, Levine, & Lowe, 2014	*Climate Dynamics*
Xia et al., 2014	*Journal of Geophysical Research: Atmospheres*
Yu et al., 2015	*Global and Planetary Change*

Table A.2: Bibliography of reviewed papers

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Table A.3: Key characteristics of scenarios in reviewed papers

Author(s)/year	Social or physical science	Category	Technological scope	Geographic scale	Time horizon	Number of scenarios	Qualitative or quantitative	Trends and/or events	Snapshot or storyline	Applies formal scenario method	Methodology	Participatory process
Izrael, Volodin, Kostrykin, Revokatova, & Ryaboshapko, 2013 *	P	1	~	~	~	~	~	~	~	~	~	~
Bala & Nag, 2012	P	1	MCB	GLOB	2082	3	QUANT	TREND	LINE	NO	DIRECT	NO
Bates, 2012	P	1	SRM	GLOB	~	2	QUANT	TREND	LINE	NO	DIRECT	NO
Boucher et al., 2012	P	1	CDR	GLOB	2292	4	QUANT	TREND	LINE	NO	DIRECT	NO
Bouttes, Gregory, & Lowe, 2013	P	1	CDR	GLOB	2312-2412	4	QUANT	TREND	LINE	NO	DIRECT	NO
Brovkin et al., 2009	P	1	SAI	GLOB	3000	4	QUANT	TREND	LINE	NO	DIRECT	NO
Caldeira & Wood, 2008	P	1	SRM	GLOB	2078	9	QUANT	TREND	LINE	NO	DIRECT	NO
Chen & Yin, 2014	P	1	MCB	GLOB	~	13	QUANT	TREND	~	NO	DIRECT	NO
Denman, 2008	P	1	OIF	GLOB	2100	5	QUANT	TREND	LINE	NO	DIRECT	NO
Eliseev, 2012 *	P	1	~	~	~	~	~	~	~	~	DIRECT	~
Korhonen, Carslaw, & Romakkaniemi, 2010	P	1	MCB	GLOB	~	3	QUANT	TREND	SNAP	NO	DIRECT	NO
Laakso et al., 2012	P	1	SAI	GLOB	2005	9	QUANT	TREND	SNAP	NO	DIRECT	NO
Laakso et al., 2016	P	1	SAI	GLOB	2020	5	QUANT	MIX	LINE	NO	DIRECT	NO
Manfready, 2011	P	1	CDR	SAHARA	~	2	QUANT	TREND	~	NO	DIRECT	NO
McInnes, 2010	P	1	SPACE	GLOB	2110	1	QUANT	TREND	LINE	NO	DIRECT	NO
Naik, Wuebbles, DeLucia, & Foley, 2003	P	1	SRM	GLOB	2103	5	QUANT	TREND	LINE	NO	DIRECT	NO
Niemeier, Schmidt, & Timmreck, 2011	P	1	SAI	GLOB	2014	8	QUANT	TREND	SNAP	NO	DIRECT	NO
Parkes, Gadian, & Latham, 2012	P	1	MCB	GLOB	2082	4	QUANT	TREND	LINE	NO	DIRECT	NO
Partanen et al., 2013	P	1	MCB	GLOB	2020	3	QUANT	TREND	LINE	NO	DIRECT	NO
Pringle et al., 2012	P	1	MCB	GLOB	2100	7	QUANT	TREND	LINE	NO	DIRECT	NO

Rasch, Crutzen, & Coleman, 2008	P	1	SAI	GLOB	2058	7	QUANT	TREND	LINE	NO	DIRECT	NO
Rasch, Latham, & Chen, 2009	P	1	MCB	GLOB	2109	4	QUANT	TREND	LINE	NO	DIRECT	NO
Rasch, Tilmes, et al., 2008	P	1	SAI	GLOB	2030	2	QUANT	TREND	LINE	NO	DIRECT	NO
Schaller, Sedláček, & Knutti, 2014	P	1	SRM	GLOB	2134	9	QUANT	TREND	LINE	NO	DIRECT	NO
Thomas et al., 2011	P	1	OIF + MCB	GLOB	2012	3	QUANT	TREND	SNAP	NO	DIRECT	NO
Vaughan & Lenton, 2012	P	1	SRM + BECCS	GLOB	2500	13	QUANT	TREND	LINE	NO	DIRECT	NO
Volodin, Kostrykin, & Ryaboshapko, 2011a	P	1	SAI	GLOB	2140	5	QUANT	TREND	LINE	NO	DIRECT	NO
Volodin, Kostrykin, & Ryaboshapko, 2011b	P	1	SAI	GLOB	2040	6	QUANT	TREND	LINE	NO	DIRECT	NO
Wigley, 2006	P	1	SAI	GLOB	2100	6	QUANT	TREND	LINE	NO	DIRECT	NO
Wu, Ridley, Pardaens, Levine, & Lowe, 2014	P	1	CDR	GLOB	2614	10	QUANT	MIX	LINE	NO	DIRECT	NO
Aswathy et al., 2014	P	1	SAI + MCB	GLOB	2100	2	QUANT	TREND	LINE	NO	GEOMIP	NO
Berdahl et al., 2014	P	1	SRM	GLOB	2100	3	QUANT	TREND	LINE	NO	GEOMIP	NO
Bürger & Cubasch, 2015	P	1	SAI	GLOB	2100	3	QUANT	TREND	LINE	NO	GEOMIP	NO
Gabriel & Robock, 2015	P	1	SAI	GLOB	2100	7	QUANT	TREND	LINE	NO	GEOMIP	NO
Jarvis & Leedal, 2012	P	1	SRM	GLOB	2100	4	QUANT	TREND	LINE	NO	GEOMIP	NO
Kravitz et al., 2011	P	1	SRM	GLOB	2100	4	QUANT	TREND	LINE	NO	GEOMIP	NO
Kravitz et al., 2013	P	1	MCB	GLOB	2100	3	QUANT	TREND	LINE	NO	GEOMIP	NO
Moore et al., 2014	P	1	SRM	GLOB	2064	3	QUANT	TREND	LINE	NO	GEOMIP	NO
Moore et al., 2015	P	1	SAI	GLOB	2100	3	QUANT	TREND	LINE	NO	GEOMIP	NO
Muri, Niemeier, & Kristjánsson, 2015	P	1	MCB	GLOB	2100	2	QUANT	TREND	LINE	NO	GEOMIP	NO
Robock, 2014	P	1	SAI	GLOB	2100	4	QUANT	TREND	LINE	NO	GEOMIP	NO
Schmidt et al., 2012	P	1	SRM	GLOB	2162	3	QUANT	TREND	LINE	NO	GEOMIP	NO
Xia et al., 2014	P	1	SRM	GLOB	2164	3	QUANT	TREND	LINE	NO	GEOMIP	NO
Yu et al., 2015	P	1	SRM	GLOB	2100	4	QUANT	TREND	LINE	NO	GEOMIP	NO
Alterskjær et al., 2013	P	1	MCB	GLOB	2100	2	QUANT	TREND	LINE	NO	IPCC	NO

Ammann, Washington, Meehl, Buja, & Teng, 2010	P	1	SAI	GLOB	2100	4	QUANT	TREND	LINE	NO	IPCC	NO
Applegate & Keller, 2015	P	1	SRM	GLOB	2100	20	QUANT	TREND	LINE	NO	IPCC	NO
Cao & Caldeira, 2010	P	1	CDR	GLOB	2500	4	QUANT	TREND	LINE	NO	IPCC	NO
Couce, Irvine, Gregoire, Ridgwell, & Hendy, 2013	P	1	CDR + SRM	GLOB	2100	4	QUANT	TREND	LINE	NO	IPCC	NO
Eliseev & Mokhov, 2009	P	1	SAI	GLOB	2100	1	QUANT	TREND	LINE	NO	IPCC	NO
Eliseev, Chernokulsky, Karpenko, & Mokhov, 2010	P	1	SAI	GLOB	2100	1	QUANT	TREND	LINE	NO	IPCC	NO
Grandey & Wang, 2015	P	1	OIF + MCB	GLOB	2100	2	QUANT	TREND	LINE	NO	IPCC	NO
Irvine, Sriver, & Keller, 2012	P	1	SRM	GLOB	2100	120	QUANT	TREND	LINE	NO	IPCC	NO
Jackson et al., 2015	P	1	SAI	GLOB	2100	2	QUANT	TREND	LINE	NO	IPCC	NO
Jones, Haywood, & Jones, 2016	P	1	SAI	GLOB	2100	4	QUANT	TREND	LINE	NO	IPCC	NO
Jones, Haywood, Boucher, Kravitz, & Robock, 2010	P	1	SAI	GLOB	2100	3	QUANT	TREND	LINE	NO	IPCC	NO
Keller, Feng, & Oschlies, 2014	P	1	SAI + OIF	GLOB	2100	5	QUANT	TREND	LINE	NO	IPCC	NO
Kwiatkowski, Cox, Halloran, Mumby, & Wiltshire, 2015	P	1	SAI	GLOB	2100	3	QUANT	TREND	LINE	NO	IPCC	NO
Llanillo, Jones, & von Glasow, 2010	P	1	SAI	GLOB	2100	10	QUANT	TREND	LINE	NO	IPCC	NO
MacMartin, Caldeira, & Keith, 2014	P	1	SRM	GLOB	2250	4	QUANT	TREND	LINE	NO	IPCC	NO
Matthews & Caldeira, 2007	P	1	SRM	GLOB	2100	11	QUANT	TREND	LINE	NO	IPCC	NO
McCusker, Armour, Bitz, & Battisti, 2014	P	1	SAI	GLOB	2100	6	QUANT	TREND	LINE	NO	IPCC	NO
Moore et al., 2010	P	1	SAI + BECCS + SPACE	GLOB	2100	3	QUANT	TREND	LINE	NO	IPCC	NO
Niemeier, Schmidt, Alterskjaer, & Kristjánsson, 2013	P	1	SAI + MCB + SPACE	GLOB	2100	5	QUANT	TREND	LINE	NO	IPCC	NO
Ricke, Morgan, & Allen, 2010	P	1	SAI	GLOB	2100	54	QUANT	TREND	LINE	NO	IPCC	NO
Robock, Oman, & Stenchikov, 2008	P	1	SAI	GLOB	2100	4	QUANT	TREND	LINE	NO	IPCC	NO

Smith & Rasch, 2013	P	1	SRM	GLOB	2200	6	QUANT	TREND	LINE	NO	IPCC	NO
Tilmes, Garcia, Kinnison, Gettelman, & Rasch, 2009	P	1	SAI	GLOB	2100	2	QUANT	TREND	LINE	NO	IPCC	NO
Tilmes, Jahn, Kay, Holland, & Lamarque, 2014	P	1	SRM	GLOB	2100	1	QUANT	TREND	LINE	NO	IPCC	NO
Tjiputra, Grini, & Lee, 2016	P	1	SAI	GLOB	2200	6	QUANT	TREND	LINE	NO	IPCC	NO
Wilhelm, Davin, & Seneviratne, 2015	P	1	SRM	GLOB	2100	7	QUANT	TREND	LINE	NO	IPCC	NO
House of Commons Science and Technology Committee, 2010	S	2	SRM	GLOB	~	~	QUAL	~	SNAP	NO	~	NO
NAS, 2015	S	2	~	GLOB	~	~	QUAL	EVENTS	SNAP	NO	~	NO
Bickel & Agrawal, 2013	S	2	SAI	GLOB	2150	5	QUANT	MIX	LINE	NO	BINARY VARIABLES	NO
Bickel, 2013	S	2	SAI	GLOB	2205	3	QUANT	MIX	LINE	NO	BINARY VARIABLES	NO
Goes, Tuana, & Keller, 2011	S	2	SAI	GLOB	2300	4	QUANT	MIX	LINE	NO	BINARY VARIABLES	NO
Parson, 2014	S	2	SRM	GLOB	~	4	QUAL	TREND	~	NO	BINARY VARIABLES	NO
CBD Secretariat, 2012	P	2	CDR + SRM	GLOB	2100	3	QUANT	TREND	LINE	NO	DIRECT	NO
Amelung & Funke, 2014	S	2	MCB	GLOB	3000	1	QUAL	MIX	LINE	NO	DIRECT	NO
Bodansky, 2013	S	2	SRM	GLOB	~	4	QUAL	TREND	SNAP	NO	DIRECT	NO
Doda, 2014	S	2	CDR + SRM	GLOB	2300	8	QUANT	TREND	LINE	NO	DIRECT	NO
Horton, 2011	S	2	SAI	GLOB	~	1	QUAL	EVENTS	SNAP	NO	DIRECT	NO
Keith & MacMartin, 2015	S	2	SAI	GLOB	2200	2	QUANT	TREND	LINE	NO	DIRECT	NO
Olson, 2011	S	2	CDR + SRM	GLOB	~	5	QUAL	TREND	SNAP	NO	DIRECT	NO
Princiotta & Loughlin, 2014	S	2	SRM	GLOB	2100	~	QUANT	TREND	LINE	NO	DIRECT	NO
Ricke, Morgan, Apt, Victor, & Steinbruner, 2008	S	2	SRM	GLOB	~	2	QUAL	EVENTS	SNAP	NO	DIRECT	NO
Rickels, Rehdanz, & Oschlies, 2009	S	2	OIF	GLOB	2100	3	QUANT	TREND	LINE	NO	DIRECT	NO
Schwartz & Randall, 2003	S	2	~	GLOB	2030	1	QUAL	MIX	LINE	NO	DIRECT	NO

STUDY SPONSORED BY BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE, n.d.	S	2	SRM	GLOB	2100	3	QUANT	TREND	LINE	NO	DIRECT	NO
Svoboda, 2012a	S	2	SAI	GLOB	~	~	QUAL	~	~	NO	DIRECT	~
Svoboda, 2012b	S	2	SAI	GLOB	~	~	QUAL	~	~	NO	DIRECT	~
Svoboda, 2015	S	2	~	GLOB	~	~	QUAL	~	~	NO	DIRECT	~
Banerjee, Collins, Low, & Blackstock, 2013	S	3	SRM	GLOB	2050-2100	6	QUAL	MIX	LINE	YES	2 AXIS	YES
Sweeney, 2014	S	3	CDR + SRM	GLOB	2034-2064	4	QUAL	MIX	LINE	YES	2 AXIS + 4 FUTURES	NO
de Larragan, 2012	S	3	CDR + SRM	GLOB	2032	5	QUAL	TREND	SNAP	YES	BINARY VARIABLES	NO
Bellamy & Healey, 2015	S	3	SAI + MCB + DACS + BECCS	GLOB	2035	8	QUAL	MIX	SNAP	YES	DELIBERATION	YES
Baum, Maher, & Haqq-Misra, 2013	S	3	SRM	REGION	~	1	QUAL	EVENTS	LINE	YES	DIRECT	NO
Haraguchi et al., 2015	S	3	SRM	GLOB	2025	2	QUAL	MIX	LINE	YES	FACTOR SYSTEM ANALYSIS	YES
Böttcher, Gabriel, & Low, 2016	S	3	SRM	GLOB	2030	4	QUAL	MIX	LINE	YES	INTUITIVE LOGICS	YES
Böttcher, Gabriel, & Harnisch, 2015	S	3	SRM	GLOB	2030	3	QUAL	MIX	LINE	YES	NARRATIVE + MORPHOLOGICAL	YES
Lempert & Prosnitz, 2011	S	3	SRM	GLOB	~	24	QUANT	TREND	SNAP	NO	RDM	NO
Milkoreit, Low, Escarraman, & Blackstock, 2011	S	3	CDR + SRM	GLOB	~	3	QUAL	TREND	SNAP	YES	RED TEAMING	YES

* could not get full access to paper
NB in physical science there is often a control or comparator scenario

Legend:

~	Could not be determined
2 AXIS	Two axis scenario method
4 FUTURES	Four futures Manoa school scenario method
BECCS	Bioenergy with carbon capture and storage
BINARY VARIABLES	Explores settings of key binary variables
CDR	Carbon dioxide removal
DAC	Direct air capture
DELIBERATION	Structured discussion around key variables
DIRECT	Direct creation and use of one or many (often simple) scenarios without justification

EVENTS	Explores only stochastic events, no trends
FACTOR SYSTEMS ANALYSIS	Cross impact balance analysis of key factors
GEOMIP	Experiments described in the Geoengineering Model Intercomparison Project
GLOB	Global
INTUITIVE LOGICS	Intuitive logics scenario method
IPCC	Scenarios described by the Intergovernmental Panel on Climate Change
LINE	Storyline scenario (rather than a snapshot)
MCB	Marine cloud brightening
MIX	Explores both trends and stochastic events
NARRATIVE + MORPHOLOGICAL	Explores key uncertainties through structured discussion
OIF	Ocean iron fertilisation
P	Physical sciences
QUAL	Qualitative
QUANT	Quantitative
DM	Robust Decision Making process
RED TEAMING	For and against gaming scenario
REGION	Regional
S	Social (or mixed) sciences
SAHARA	Sahara focus
SAI	Stratospheric aerosol injection:
SNAP	Snapshot scenario (rather than a storyline)
SPACE	Space-based
SRM	Solar Radiation Management
TREND	Explores only trends, no stochastic events

Table A.4: Scenario types used in the physical science papers

Scenario		Number of papers
SRES		12
	A1B	8
	A2	4
RCP		29
	RCP2.6	2
	RCP4.5	21
	RCP6.0	2
	RCP8.5	11
Total of either RCP or SRES		41
Two- or four-times step increase in CO2 concentration		18
GeoMIP		14
	G1	9
	G2	6
	G3	11
	G4	9
Scenario includes termination effect		18
Total		71
Note: the numbers do not add to 71. This is because one paper may contain several scenarios that meet multiple criteria in which case they are counted multiple times.		

Scenario details in:

Kravitz, B., Robock, A., Boucher, O., Schmidt, H., Taylor, K.E., Stenchikov, G., Schulz, M., 2011. The geoengineering model intercomparison project (GeoMIP). Atmospheric Sci. Lett. 12, 162–167.

Moss, R., Babike, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J., Elgizouli, I., Emori, S., Erda, L., Hibbard, K., Jones, R., Kainuma, M., Kelleher, J., Lamarque, J.-F., Manning, M., Matthews, B., Meehl, J., Meyer, L., Mitchell, J., Nakicenovic, N., O'Neill, B., Pichs, R., Riahi, K., Rose, S., Runci, P., Stouffer, R., van Vuuren, D., Weyant, J., Wilbanks, T., vanYpersele, J.-P., Zurek, M., 2008. Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies, Technical Summary. Intergovernmental Panel on Climate Change, Geneva.

Nakicenovic, N., Swart, R., 2000. Special report on emissions scenarios. Spec. Rep. Emiss. Scenar. Ed. Nebojsa Nakicenovic Robert Swart Pp 612 ISBN 0521804930 Camb. UK Camb. Univ. Press July 2000 1.

Table A.5: Scenario methods or key determinants used in papers that employ a deliberate scenario technique or define explicit scenarios

Paper	Scenario methodology	Scenario building blocks (assumptions and determinants)
Baum, Maher, & Haqq-Misra, 2013	A formal method was applied but no reference for that method was provided.	SRM is deployed, there is societal collapse and SRM is terminated. Key factors are: -How SRM is implemented: regional or global coalition, shock event (nuclear, weather, war) -Whether emissions increase or decrease after SRM.
Sweeney, 2014	Fuses the 2X2 scenario modeling technique (Ramirez & Wilkinson, 2013) with the "Manoa School" four-futures method (Dator 2009).	All geoengineering technologies are treated as one decision factor in this exercise. The two axes are defined as 'control' and 'command', but the meanings and poles of these are not clear. The key drivers are (as in the Manoa School) are: -Population -Energy availability -Type of global economy -Treatment of environment -Type of culture -Level of technology development -Type of governance
de Larragan, 2012	Legal analysis using five scenarios. A formal method was applied. It relied on the identification of key variables and derived scenarios from combinations of these. However, no reference for the method was provided.	The term 'geoengineering' is used generically. Key determinants of the scenarios are: -Degrees of global coordination (and whether inside or outside UNFCCC process); -Effectiveness of emissions reduction efforts (and whether focussed on mitigation or adaptation)
Banerjee, Collins, Low, & Blackstock, 2013	The Two-Axis Scenario Method (Ogilvy 2002, 2011)	Only SRM is considered. The two axes are defined as 'SRM is controllable/uncontrollable' on one axis and 'self-interested nations/global good' on the other axis. Two additional scenarios consider non-deployment against the variable of controllability. Possible disruptive events that are also discussed are volcanic eruption, tipping point triggered, pandemic leads to reduced economic growth and therefore emissions, global economic collapse, collapse of international institutions, and game-changing renewable technologies.
Lempert & Prosnitz, 2011	Robust decisionmaking (RDM) analysis (Bryant and Lempert 2010) using Bayesian networks. Scenarios are created as combinations of four exogenous uncertainties each with two or three settings.	Exogenous uncertainties: -Severity of climate change (catastrophic, severe, or mild) -Technical potential for geoengineering (likely or unlikely) -Potential for agreements (favourable or unfavourable) -Influence of geoengineering on emissions (strong or weak)

Böttcher, Gabriel, & Harnisch, 2015	No reference is provided for technique employed. It is a combination of narrative building and morphological analysis. A first round of group-based brainstorming scanning produced about 100 relevant factor, of which eight were voted as critical using an impact/uncertainty matrix. Three projections of each of the factors were created in small group. Morphological analysis techniques were used to combine the projections into four scenario outlines. Three of these were then fleshed out by smaller groups.	Only SRM is considered. Specific uncertainties are not disclosed in the report, but were provided by the author on request as: -'Doer and Opposer' states -How crisis is perceived and whether uniformly -Societal acceptance of SRM -International governance of SRM -Aim of SRM deployment (targeted, temporary…) -Existence of (efficient) SRM technology -Major shift in global power balance -Mitigation and CDR technologies
Bellamy & Healey, 2015	No reference for method provided. Experts were given combinations of SRM and CDR technologies and asked to develop 20-year timelines for geoengineering research reflecting on the roles of self-regulation, global governance, principles and protocols, and a moratorium.	Determining variables: -Four technologies: direct air capture (DACS); bioenergy with carbon capture and storage (BECCS); stratospheric aerosol injection (SAI); marine cloud brightening (MCB) -Four governance models: self-regulation; global governance; principles and protocols; and a moratorium -Technology development: maturity of technology, potential for breakthrough, predictability of impacts Key uncertainties: -DACS: climate change impacts as motivation or exit strategy for SRM termination, carbon price, NIMBY as opposition, relative success of CCS. -BECCS: as short-term only, carbon price, tehcnology breakthrough, possibility for China where there is a lot of land, hinges on public support (linked to good regulation, to whether associated with mitiagation or geoengineering, to renewable energy costs, to land-use impacts and to food security) -SAI: possible ban on deployment but continued R&D, buy time, risk of unilateralism, or coalition of the willing, compensation, 'counter-geoengineering', feasibility, relative importance of damage from ocean acidification, carbon price. -MCB: either ban on deployment by 2030, depends on success of testing and impact attribution, perceptions of risk, feasbility, viability, reversibility, management of moral hazard.
Haraguchi et al., 2015	Factor-System Analysis and Scenario Construction (no reference provided): (1) collect and investigate drivers (2) perform factor-system analysis to distill the most crucial factors (3) construct two scenarios (4) derive implications and policy options	Only SRM is considered. Factors identified were (key ones used for scenarios in bold): -Public awareness of geoengineering -NGO engagement -UNFCCC negotiations -Research cooperation on geoengineering -Industry interest in investing in geoengineering -Degree of institutionalisation and formalisation of a governance framework -Number or severity of climatic natural disasters -Impact of geoengineering on water- food-energy systems -Geoengineering test results -US view regarding geoengineering research, funding and governance -EU view regarding geoengineering research, funding and governance -Global emissions -Geopolitical dynamics -BRICS (Brazil, Russia, India, China, South Africa) view regarding geoengineering research, funding and governance

Milkoreit, Low, Escarraman, & Blackstock, 2011	Red Teaming (Lauder 2009): Three teams are given an agenda each and asked to role-play appropriate actors and strategies.	No explicit distinction is made between SRM and CDR. Key factors are seen as agenda, actors, framing, influence and persuasion and engagement within or outside the existing international organisation landscape. Key limitations cited were the lack of interaction between teams or actors and the absence of a developing country actor in the exercise.
Böttcher, Gabriel, & Low, 2016	A computer-aided multistep process consisting of: (1) scanning for drivers (2) identifying uncertainties (3) narrowing to key uncertainties (4) projecting four possible outcomes of each key uncertainty (5) generating scenario frameworks from all combinations of projections (8^4) (6) reducing scenario frameworks to only those that are internally consistent (computer-aided) (7) selecting from these four scenario frameworks	Only SRM is the focus but sustained SRM deployment is not considered. Key uncertainties are: -Perception of climate change -Domestic and regional stability -CDR technology advancement -Mitigation technology advancement and emissions pathways to 2030 -US-China relationship -Acceptability of SRM -Methane feedback and climate sensitivity/impacts -Global economic stability

Details in:

Bryant, B.P., Lempert, R.J., 2010. Thinking inside the box: A participatory, computer-assisted approach to scenario discovery. Technol. Forecast. Soc. Change 77, 34–49. doi:10.1016/j.techfore.2009.08.002

Dator, J.A., Sweeney, J.A., Yee, A.M., 2015. Alternative Futures at the Mānoa School, in: Mutative Media, Lecture Notes in Social Networks. Springer International Publishing, pp. 133–151. doi:10.1007/978-3-319-07809-0_5

Lauder, M., 2009. Red dawn: The emergence of a Red Teaming capability in The canadian forces. Can. Army J. 12, 25–36.

Ramirez, R., Wilkinson, A., 2014. Rethinking the 2x2 scenario method: Grid or frames? Technol. Forecast. Soc. Change 86, 254–264. doi:10.1016/j.techfore.2013.10.020

Ogilvy, J., 2002. Creating better futures. Scenar. Plan. Tool Better.

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Appendix B – Full narratives of the scenarios

Corporatocracy

A growing and continuously-developing global economy fuels urbanisation and high population growth. This sees in 2050 a world with 10.9 billion inhabitants highly concentrated in megacities, where energy demands are high.

As the State has continued its transition from the ‘welfarist’ model of the 20th century to widespread privatization, corporates now hold strong influences over global and national economies. Governments have outsourced most of their service delivery. Corporations now provide the police service in many countries, the national media regulating service, and the delivery of welfare.

In this strong global economy, the culture is heavily consumerist. Technology development is continually accelerating, driven in part by the constant demand for novel products. Cultures that see themselves as integrated and connected to nature have been increasingly marginalized or disempowered. This has resulted in a loss of knowledge about the natural world and harmonious ways to interact with it. In 2050, the natural environment is not so natural. Given the detachment of this population from ‘nature’, they readily accept brave new technologies. Desalination plants, monoculture plantations, and new or diverted rivers are commonplace.

At the same time, trust levels between government (that are now seen to serve corporations) and the people are at historical lows, but the relatively high standard of living of the majority of the population stymie any real uprisings. Despite evidence of localised public agitation, there are no major transformative or disruptive forces to the political system because corporations effectively ‘own’ political parties. The reform agenda is increasingly dictated by the corporations that support the major parties. A sense of political stability seems to permeate.

The Paris Agreement began to transform climate change from a longer-term threat to the economy (through its physical impacts) into a short-term threat to corporations (through policy-accelerated economic transition risks). Corporations, due to a combination of profit-seeking and moral duty, have seen a notable shift over the past decades with directors and boards taking climate change into consideration in decision-making. Change is underway, but the transition is initially slow and steady, heavily controlled to maximise upside risks and minimise downside risks for corporations. This allows large corporations to diversify their operations but maintain profitable fossil-fuel investments until they reach maturity. They methodically siphon some of those profits into clean technology investments to profit from emerging markets.

However, the trend eventually takes on its own momentum as the clean technology industry begins to demonstrate genuine medium-term economic benefits. As a result, the clean technology industry begins to dominate. There is gradual introduction of a hydrogen economy based on a gasification of biomass grown in fertilized oceans. Global energy is sufficient. Carbon concentrations have begun to stabilize but because the transition was initially slow, the 2°C threshold was not avoided. It has become increasingly difficult to feed the growing population. Strong agricultural conglomerates push for a more effective Paris Agreement that reflects the measurable outcomes mentality of the Corporatocracy. The Paris Agreement is amended deleting all references to greenhouse gas emissions and atmospheric carbon concentrations, both of which are difficult to monitor and verify. Instead, the Paris Agreement is amended to aim only for temperature reductions. This ultimately justifies the use of solar geoengineering to create a climate where agriculture can feed 11 billion people. The climate, like the rest of the environment, becomes controlled, artificial and conquered.

However, as is inevitable, inequality rises both within nations and between nations as only certain sections of the global population have the opportunity to hold decision making positions in key corporations. There exists an undercurrent of social resistance in those countries where the population still holds some faith in representative democracy and the need for those in charge to listen to the people. These countries most likely have also missed out on the highest levels of economic growth, which has further fuelled the uprisings and resistance. The technologies that have been developed are maintaining a ‘survivable’ planet but are increasing the need to continually manipulate the environment. These social pockets of resistance are spread across the globe.

Led by environmental movements and indigenous rights activists, a grassroots campaign starts convincing communities to reject a society controlled by undemocratic profit-seeking (no matter how 'benevolent') corporations, and to join the creative and destructive project of imagining and building a new way to organise society. An opportune window appears for these campaigners as solar shields begin to fail. How will this play out? Will the (corporately-sponsored) military step in to quash resistance and to protect the climate management infrastructure? Will society collapse as the geoengineering technology crumbles and as resistors, equipped with only social capital, resort to violence (people power) to force change? Or will these resistors, having managed to raise sufficient financial capital, invest in society-changing initiatives and win back the power establishing more direct forms of governance and doing away with geoengineering all together?

Corporatocracy in Australia

In Australia, the population readily accepts the Corporatocracy. Popular social reforms like same-sex marriage have been promoted (and passed through parliament) because corporates targeted these issues to appease the population while they increase their control of the economy and society in general. The reform agenda is increasingly dictated by the corporations. Senate rules are being amended to reduce the influence of disruptive independents. This plays into the hands of larger parties (backed by corporates) that then ensure that corporate-friendly agendas are passed through parliament.

Following the success of the Paris Agreement, emissions intensive corporations must diversify their operations away from fossil fuels to remain internationally competitive. The question is whether Australian corporations will be able to ride the wave of economic transformation and remain strong and prosperous into the future. The prominence of corporations drives and defines society and the economy. Therefore, it will be the ability of Australian corporations to transform that will dictate how powerful Australia as a nation remains over coming decades. This has implications for how directly involved Australian corporations (and by extension Australia overall) is in setting global reform agendas.

The Purge

Over time, an engrained culture of short-termism negatively impacts on the ability of governments and corporations to proactively manage complex longer-term risks, such as those presented by climate change. This endemic short-termism leads to failure of the Paris Agreement to catalyse meaningful emissions reductions across the global economy.

Temperatures soar due to rising greenhouse gas emissions. A series of extreme climate events in close succession caused by worst-case scenario global warming create recessionary conditions across the global economy. These events occur within a context of perpetually high levels of public and private debt. The stalling of economic growth triggers multiple corporate defaults because record debts cannot be serviced in the recessionary environment. This in turn creates a systemic crisis, triggering the collapse of the global economy.

At the same time, intra- and inter-state conflicts over increasingly scarce natural resources become more frequent and violent. The confluence of economic calamity and adverse physical impacts of climate change cause food supply chains to fail and disease to become widespread. Political tensions are high. Populations are weakened and significantly reduced because they are now much less resilient to the impacts of natural disasters. There is no capital available for innovation or invention whether for health, environmental or other reasons. The collapse in economic activity leads to a plummet in greenhouse gas emissions, but atmospheric concentrations are already high.

This world is in crisis. Although the backbone of inter-state communication and basic diplomacy still remain, States turn inwards. Many of these succumb to authoritarian regimes. In the United States certain states (such as California and Texas), governed by strong centralised political authorities declare political independence from the federation and begin to rebuild.

Political communities are fragmented but despair and collapse is not evenly distributed with populations in urban areas having the lowest levels of resilience. In most states, the welfare state has been nearly entirely abandoned. Some pockets of civilisations and individuals within civilisations manage to take advantage of the situation. These ‘survivalists’ thrive. These are people that had always eked their own living, never dependent on insurance companies to bail them out or on handouts from governments when disaster obliterated their worldly possessions. Rural areas are where the world begins again, building from a clean slate. Small agricultural ventures begin to appear across landscapes. Some decentralised energy systems are able to continue functioning but in an unreliable manner. There is a revival of semi-autonomous rural colonies as cities collapse. Population patterns undergo big changes– structures begin again to resemble ancient times.

Countries with political systems that favour longer-term planning, such as China or Russia, weather the crisis best. Although somewhat altered, their political cultures remain strong and in 2050 they lead the world.

The Purge in Australia

Australia’s action to mitigate the physical impacts of climate change over coming decades is, like the rest of the world, frustrated by short-termism. In Australia, rainfall patterns become extremely erratic. Prolonged droughts and heatwaves turn the lucky country into a dustbowl. Droughts are broken only by intense storms and floods that wash away any remaining utilities, infrastructure and livelihoods. Virtually no ecosystem is left untouched by climate change; most are destroyed completely or overrun by weeds and pests that opportunistically colonised after the disturbances.

Physical and human damage of extreme climate events become catastrophic, and financial costs unsurmountable. Australian insurance companies collapse. The bill for repairing the damage fall far beyond what governments can afford. It doesn't take long for Australian agricultural and mining industries, vulnerable to disasters and heavily dependent on water, soils and other natural resources, to fold. Vast tracts of once prime agricultural land in the north are now marginal and have been abandoned. Centralised energy systems are damaged and dysfunctional, and pollution in town water supplies has rendered tap water unsafe for drinking.

The southern parts of Australia present a few places left that are still viable for cropping. Dotted across these regions, small farms begin to appear and link. By this stage, the Australian government is weak and decentralised. The government has limited influence over what is effectively an array of semi-autonomous colonies linked to small decentralised grids. These communities rebuild from the ground up.

'1984'

A series of extreme weather events around the world causes damage that exacerbates costs of living in several countries. Insurance premiums rise to excessive levels. People in exposed locations can no longer afford to insure their assets. In some locations insurance companies no longer offer cover. This brings climate action into political focus globally. The world begins to consider shifting away from commodities that had been the mainstay of economies over the previous two and a half decades (metallurgical and thermal coal, iron ore and natural gas). This leads to the proliferation of stranded assets over many sectors and the impending collapse of some major banks and multinational investment funds that were too slow to diversify. In a number of countries, national governments are required to step in to guarantee customer deposits. At the same time because of their increased exposure to risk, asset values begin a rapid decline, eroding consumer confidence. Governments are again required to step in but find themselves limited in their capacity to stimulate the economy. A period of economic contraction ensues.

By 2050, economies around the world are characterised by low growth, high unemployment and record government debt. To recoup their debt, some governments impose high taxes. In these nations, intergenerational angst develops as the youth resent the restriction of their opportunities and having to forgo large amounts of their income to taxes to pay down government debt. Unconventional monetary policies, such as printing money, become the norm to keep the system afloat.

With the move away from fossil fuels and the collapse of some sectors, atmospheric carbon concentrations have begun to stabilise. However, climate sensitivity and feedforward mechanisms have proven higher than anticipated. Governments work closely with banks and insurance companies to further joint interests, prioritising and co-funding climate adaptation efforts that are strictly implemented and accountable to objective criteria. New and innovative infrastructure is created for climate adaptation generating mass employment opportunities and is thus widely supported by local communities. For example, artificial reefs replace natural reefs to ensure that marine ecosystems are not lost and to provide new revenue streams (fisheries, tourism etc.).

However, severe weather events are still frequent and adaptation is not deployed fast enough or at the scale required. Reduced resilience leads to localised population collapse, which stalls global population growth. Mitigation has been too late and geoengineering has become the one last hope. People accept that geoengineering is the only hope of avoiding total collapse of Civilisation (which has already manifested itself in many locations around the world leading to the movement of millions of displaced people each year).

Rich countries of the world deploy geoengineering technologies. Citizens of the world unite in their hope that this technology will work. The few dissenting voices are rapidly silenced. The management of geoengineering is recognised as far too important to be subject of partisan localised politics. The United Nations (or equivalent body) oversees the technology's global deployment. National governments are increasingly recognised as subservient to this form of supreme governance. Geoengineering is 'rebadged', like the artificial reefs, as a way to prioritise and protect natural ecosystems until such time as temperatures are brought down to manageable levels. It is also recognised as an economic growth platform.

This increased awareness of the need for rapid carbon emissions reduction and drawdown, the culture shifts to one where nations are no longer compared on the metrics of GDP but on natural capital accounting and resilience. Top-down emissions and energy budgets are imposed at the national and subnational scales, driving the proliferation of carbon dioxide removal technologies. Population policies are implemented in many countries to help meet environmental targets. Tariffs are applied to all goods that embody carbon emissions; organisations are required to undertake cost-benefit analyses and lifecycle assessments that incorporate environmental values. High taxes are placed on meat to account for its social and environmental costs. People increasingly adopt plant-based diets with meat seen as a luxury food item and older members of the community nostalgic about the 'good old days' when meat was eaten most nights. The circular economy is no longer an option but a requirement.

Despite its perceived success this totalitarian governance approach is inherently vulnerable and unstable. Strong black markets develop trading in carbon-intensive products and in technologies that exploit carbon accounting loopholes. Protest political movements begin to appear, challenging the 'command economy' and its long-term sustainability.

'1984' in Australia

Australia's economy undergoes an extended period of fluctuation between low growth and recession as the world has ceased to value its primary export products. Despite perpetuating a strong rhetoric of proactively de-risking its portfolio against climate change risks, one of the Big 4 banks fails. The Federal government bails it out. Each year, Australia is saddled with at least half a dozen extreme weather events that are scientifically proven within days of the event to be due to a warming climate. Australian costs of living increase further.

The collapse of Rupert Murdoch's media empire opens up a new phase in Australian media. Support for action on climate change in Australia is strong. The government seizes on the opportunity to embed its ambitious policies on climate change mitigation. The Australian 'clean tech' economy finds its niche in renewable energy and energy efficiency. Australia also begins to experiment with genetically engineered crops. The research is not overly questioned or resisted by the community, which is burdened by record high food prices. Australia joins with other rich nations in deploying geoengineering.

Spaceship Earth

Technology now permeates everything. Everything you could need to learn or use is available online. With it comes change, such as novel GM foods and robot cities. Artificial intelligence is embedded everywhere. The human body now has so many artificial elements added to it that the boundary between human and non-human is blurred. In developed nations, humans move toward a more cyborg-like existence: naturally applying problem-solving efficiently and effectively, making 'wise' decisions, but also becoming more indifferent to 'nature'.

The concepts of family with children and of work are changed from what they were traditionally. Education levels have increased, especially for women. As a result, the global population peaks and declines. The global population naturally reduces its greenhouse gas emissions to near-zero by 2050. The Paris Agreement is no longer needed.

Humans are living longer. Although globalisation has continued, with it has developed a societal appreciation of collective global security. Scientific and technological advancements are tuned into complexity theory, and a deep appreciation of the limits of human attempts to manipulate and predict the outcomes of complex, non-linear and dynamical systems and a keen understanding of the presence of persistent 'unknowables'. At the same time, given the changed nature of humans, the relationship with the Earth is seen as symbiotic rather than harmonious.

Coming from this perspective, the Sustainable Development Goals are renewed and achieved. Carbon dioxide removal is widespread, colonising Mars and other planets is considered to be part of the near future. Energy is abundant because of the use of renewable sources, carbon capture and storage, and energy efficiency.

Plants and crops are 'engineered' to maximise root growth. Agricultural staples such as wheat and sugar, which are harvested annually, are engineered to draw down more carbon. The sucrose is then converted to protein in high-tech chemical factories to feed the population, with flavours to suit all palates. To maintain the required growing conditions, solar geoengineering is rolled out. Geoengineering becomes a tool for achieving a controlled clean atmosphere and climate stability to grow the 'new' foods.

By 2050 there is a treaty strictly regulating any form of solar geoengineering. It came after long negotiations that brought together principles and ideas from the Convention on Long-range Transboundary Air Pollution, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, the Vienna Convention for the Protection of the Ozone Layer and Montreal Protocol on Substances that Deplete the Ozone Layer, the Paris Agreement and the Nuclear non-proliferation treaty. To ensure that its strict rules are observed the treaty includes independent inspection of facilities as part of a verification process, applied to all solar-geoengineering. Carbon dioxide removal is far less regulated.

There is also a UN Security Council overlay. The treaty interfaces with the Geneva Convention and the Laws of Armed Conflict. For geoengineering above the Karman line, there is an overlay with the UN Space Treaties, particularly the Convention on International Liability for Damage Caused by Space Objects.

Spaceship Earth in Australia

Australia, with its technological advancement and early adoption of information technology, takes on a soft leadership role in this world. Australia's vulnerability to climate change sees increasing engagement in mitigation, adaptation and climate intervention. It recognises and capitalises on the potential of its abundant wind and solar energy resources. Australia is also a pioneer and strong adopter of carbon dioxide removal, because of the significant amount of available land and territorial seas relative to smaller and more populous countries.

Australia continues to value its US alliance above all others and therefore hitches its star to US initiatives on geoengineering as part of a balancing effort against what is a much more powerful China.