‘Opening up’ geoengineering appraisal: Deliberative Mapping of options for tackling climate change

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Abstract

Deliberate large-scale interventions in the Earth's climate system, known collectively as climate 'geoengineering', have been proposed in order to moderate anthropogenic climate change. A host of normative rationales for geoengineering has led to a growing number of appraisals to evaluate the different proposals and provide decision support. This thesis critically reviews current appraisals of geoengineering before developing and executing its own appraisal methodology in response to their limitations. These limitations concern: (1) the appraisal of geoengineering proposals in 'contextual isolation' of alternative options for tackling climate change; (2) inadequate methodological responses to the 'post-normal' scientific context in which climate change and geoengineering resides; and (3) a premature 'closing down' upon particular geoengineering proposals, principally stratospheric aerosol injection, through the exertion of power via framings. This thesis exhibits the findings of an 'upstream' participatory appraisal of geoengineering called Deliberative Mapping; an innovative analytic-deliberative methodology designed to 'open up' appraisal inputs and outputs to a broader diversity of framings, knowledges and future pathways. A diversity of international experts and stakeholders from across academia, civil society, industry and government, and of sociodemographically representative citizens from Norfolk (UK), were engaged using a combination of analytic Multi-Criteria Mapping specialist interviews and deliberative citizens' panels, as well as a joint specialists-citizens workshop. The results present a radically different view to other appraisals of geoengineering, where: (1) geoengineering proposals are most often outperformed by mitigation options, with stratospheric aerosol injection ranking particularly poorly; (2) a greater diversity of perspectives and assessment criteria spanning the natural, applied and social sciences reveals considerable uncertainties in all areas of research and decision making; and (3) four propositions for governance emerge that advance sociotechnical foresight, technology control and public consent, the anticipation and alleviation of impacts, a demonstration of robustness, and ultimately, the responsible innovation of geoengineering.

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their eternal love, support and encouragement

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'Power is everywhere'

– *Michael Foucault (1998: 63)*

Chapter 1

Introduction

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) has reaffirmed that warming of the global climate system is 'unequivocal' (IPCC, 2013). Changes have been observed throughout the system, with Earth surface temperature having increased by 0.85°C between 1880 and 2012. This increase has been joined by a host of other global changes in the cryosphere and oceans, spanning significant decreases in glaciers, ice sheets and snow cover and significant increases in sea temperature, level and acidification. At the same time, atmospheric concentrations of greenhouse gases have risen, and in particular those of carbon dioxide (CO_2), methane, and nitrous oxide, the levels of which are *'unprecedented in at least the last 800,000 years'* (IPCC, 2013: 9). CO_2 concentration has reached 391ppm and risen by 40% since the onset of the industrial revolution, principally as a result of fossil fuel combustion and land-use change, and is the main driver of the positive radiative forcing.

With emissions of the greenhouse gases set to continue, future changes are projected for the climate system. Earth surface temperature is likely to exceed 1.5°C by 2100 relative to between 1850 and 1900, and could be as high as 4.8°C relative to between 1986 and 2005 (IPCC, 2013). These are set to be accompanied by further changes in the atmosphere, cryosphere and oceans, including increases in the frequency and intensity of extreme heat and precipitation events, decreases in glaciers, ice sheets and snow cover, and increases in sea temperature, level and acidification. Changes in large-scale Earth systems, or 'tipping elements' are also projected, including an intensification of the El Niño Southern Oscillation, and a weakening of the Atlantic Meridional Overturning Circulation (AMOC). With sufficient external forcings, these highly nonlinear elements are at risk of passing their 'tipping points': *'the critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system'* (Lenton *et al.*, 2008: 1786). Some of these abrupt transitions, such as a collapse of the AMOC, are considered very unlikely to occur before 2100 (IPCC, 2013), whilst others, such as the disappearance of Arctic summer sea ice, may already be underway (Lenton, 2012).

The changes in climate projected by the IPCC have been established using four Representative Concentration Pathway (RCP) scenarios, defined by the radiative forcing (W/m^2) brought about through anthropogenic greenhouse gas emissions (van Vuuren *et al.*, 2011). They range from RCP2.6 which depicts a peak in radiative forcing at 3 W/m^2 before declining to 2.6 W/m^2 by 2100 (~490ppm CO_2 eq.), to RCP4.5 which depicts stabilisation at 4.5 W/m^2 after 2100 (~650ppm CO_2 eq.), to RCP6 which depicts stabilisation at 6 W/m^2 after 2100 (~850ppm CO_2 eq.), to RCP8.5 which depicts rising radiative forcing to 8.5 W/m^2 by 2100 (~1370ppm CO_2 eq.). What is interesting is that two of the RCPs assume that CO_2 concentration will be reduced not only by reducing emissions, but also by removing CO_2 from the atmosphere by using large-scale afforestation (RCP4.5) and bio-energy with carbon sequestration (RCP2.6), in addition to *'other technologies that may remove CO_2 from the atmosphere'* in Extended Concentration Pathway (ECP) 3PD (*ibid*: 25).

These technologies that remove CO_2 from the atmosphere comprise part of a new category of options for tackling climate change: climate 'geoengineering', which sits alongside the more conventional 'mitigation' (reducing greenhouse gas emissions) and 'adaptation' (reducing climate change impacts) options. As the only RCP projected to keep global temperature below *'dangerous anthropogenic interference'* (UNFCCC, Article 2, 1992) beyond 2°C, RCP2.6 is implicit in its suggestion that this objective cannot be accomplished without the use of such technologies. Indeed, it was frustrations with insufficient mitigation efforts that has led to interests in the idea of geoengineering after Nobel laureate Paul Crutzen proposed artificially enhancing the Earth's albedo through stratospheric aerosol injection (Crutzen, 2006). It has since continued to gain prominence, most recently featuring as the coda in the IPCC AR5 Summary for Policy Makers. Despite this recent and growing interest, however, geoengineering has a much longer history.

1.1 A History of Climate Control

The idea of control over the Earth's weather and climate predates the modern concept of 'geoengineering' by millennia (Fleming, 2010). It has a rich history in ancient mythologies and religions, including those of Ancient Greece and the Roman Empire. Once powers bestowed by gods, control over weather and climate is now sought through technology. Indeed, this hubristic shift in humanity's relationship with nature was presaged by renowned physicist of Ancient Greece, Archimedes, who is believed to have said: 'Give me a lever long enough and a place to stand, and I will move the world'. Much later, and following the discovery of the greenhouse effect in 1824 by Joseph Fourier and its later experimental demonstration by John Tyndall; in 1908 Svante Arrhenius proposed deliberately enhancing the greenhouse effect by burning more fossil fuels to enhance agricultural productivity (Arrhenius, 1908).

Political as well as academic interests in potential weather and climate control ensued during the early-to-mid Twentieth Century, reaching its height in the Cold War between the United States of America (USA) and the Union of Soviet Socialist Republics (USSR). During that time climate modification, and in particular weather modification, became a research and development priority for both nations, alongside heavy investments in other demonstrations of technological prowess including space exploration. The USA, for example, underwent weather optimisation efforts to weaken the destructive power of hurricanes through silver iodide cloud seeding during 'Project Stormfury' (Willoughby *et al.*, 1985). Although receiving less attention than weather modification by both governments, the USSR's climate modification research was far more extensive than the USA's and comprised proposals that included forming Saturn-inspired metallic aerosol planetary rings, and the removal of Arctic sea ice (Rusin & Flit, 1960) to foster temperate equatorial and polar climates respectively.

For the USA, the applications of weather modification took a more sinister turn during the Vietnam War. Research no longer solely sought to optimise weather, but also to weaponise it. The military began the extensive cloud seeding programme 'Operation Popeye' in Vietnam with the objective of causing heavy rainstorms to disrupt Vietcong supply lines. The controversy that followed and was sustained by the emergent environmental movement led to the signing of the United Nations international treaty, the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD) (United Nations, 1976). The convention, combined with the relative failure of cloud seeding experimentation, ultimately led to a collapse in weather modification research and development (Keith, 2000).

The convention, however, specifically reserved the entitlement to use weather and climate modification 'for peaceful purposes' (Article 3.1), helping to maintain modest academic and political interest following the discovery of anthropogenic greenhouse gas-induced climate change in 1960 by Charles Keeling. Interestingly, climate modification was proposed as a means of tackling climate change in the influential 1965 environmental policy assessment report to President Lyndon B. Johnson: *'The climatic changes that may be produced by the increased* CO_2 *content could be deleterious from the point of view of human beings. The possibilities of deliberately bringing about countervailing climatic changes therefore need to be thoroughly explored'* (PSAC, 1965: 127). Indeed, there was then no mention of what has now become the dominant, even totalising, policy discourse of mitigation (Keith, 2000).

1.2 Defining 'Geoengineering'

The term 'geoengineering' was coined in the early 1970s by Italian physicist Cesare Marchetti and later formally published in the inaugural issue of the journal Climatic Change to describe a method for the 'disposal' of atmospheric CO_2 through its injection into sinking thermohaline oceanic currents (Marchetti, 1977). The term is a compound noun derived from the prefix 'geo' from the Greek gê meaning 'Earth'; and the noun 'engineering' meaning the 'application of science to design' (OED, 2008). Previously confined to the epistemic discourses of Earth System Science and related academic disciplines, in June 2010 the term was considered to warrant a common definition in the Oxford English Dictionary. However, defining geoengineering is of course somewhat more complex than the Oxford English Dictionary's modest offering (see Table 1). This section begins to map out the complex etymology of the term, revealing ambiguities as to what constitutes geoengineering, how the term is used and competed with, and how its constituent proposals are demarcated.

Table 1.1. Selected definitions of geoengineering (redrawn from Bellamy *et al.*, 2012).

Source	Definition of geoengineering
NAS (1992: 433)	'[Geoengineering proposals] involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry'
Keith (2000: 245, 247)	'Geoengineering is the intentional large-scale manipulation of the environment… For an action to be geoengineering, the environmental change must be the primary goal rather than a side effect and the intent and effect of the manipulation must be large in scale, e.g. continental to global… Three core attributes will serve as markers of geoengineering: scale, intent and the degree to which the action is a countervailing measure'
Barrett (2008: 45)	'[Geoengineering] is to counteract climate change by reducing the amount of solar radiation that strikes the Earth… [not] by changing the atmospheric concentration of greenhouse gases'
AMS (2009: 1)	'Geoengineering – deliberately manipulating the physical, chemical, or biological aspects of the Earth system [to reduce the risks of climate change]'
Royal Society, The (2009: ix)	'The deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming'
OED (2010)	The deliberate large-scale manipulation of an environmental process that affects the Earth's climate, in an attempt to counteract the effects of global warming'

The one element that is common to these definitions is that for an action to constitute geoengineering, it must be large in scale. Most of the definitions consider this action to be in relation to tackling climate change, but it has also been used more broadly to describe the manipulation of the environment at large. Keith (2000) provides a somewhat more precise definition of geoengineering by outlining three definitional markers: scale, intent, and the extent to which an action is a countervailing measure. On the other hand, Fleming (2010) argues that those latter two markers should not be used to constrain actions already defined by their scale, and which could lead to undesirable as well as desirable countervailing ends. Indeed, anthropogenic climate change itself has been considered to be inadvertent geoengineering (NAS, 1992).

The Royal Society's (2009) seminal report *'Geoengineering the climate: science, governance and uncertainty'* has provided perhaps the most widely accepted definition of geoengineering, having been reaffirmed by the Government of the United Kingdom (UK) (HoCSTC, 2010) and the IPCC (IPCC, 2010) amongst others. However, geoengineering is competing with a host of alternative terms, including 'climate engineering' (e.g. Bodansky, 1996); 'climate modification' (e.g. McCormick & Ludwig, 1967); 'Earth systems engineering' (e.g. Schneider, 2001); 'planetary engineering' (e.g. Hoffert *et al.*, 2002); and 'climate remediation' (e.g. BPC, 2011). This latter term, 'climate remediation' is an interesting case as it represents an attempt to 'rebrand' geoengineering. It was chosen by some to sit more comfortably alongside mitigation and adaptation, but it did not go unopposed in its adoption (Sarewitz, 2011).

Geoengineering proposals are commonly divided amongst two subset classes, which themselves are competing with alternative terms. First, 'carbon geoengineering' proposals are those that seek to remove and sequester CO_2 from the atmosphere, and have also been referred to as 'Carbon Dioxide Removal' (CDR) methods (Royal Society, 2009); 'Negative Emissions Technologies' (NETs) (e.g. Kraxner *et al.*, 2003); and most recently, 'Greenhouse Gas Removal' (GGR) methods (Boucher *et al.*, 2013); the latter two of which provide space for the inclusion of technologies that seek to remove greenhouse gases other than CO_2. Second, 'solar geoengineering' proposals are those that seek to increase the reflection of sunlight back into space, and have also been referred to as 'Solar Radiation Management' (SRM) methods (Royal Society, 2009) or, under another attempt to 'rebrand' geoengineering, the less provocative 'Sunlight Reflection Methods (also, SRM) (SRMGI, 2011). Others have simply used 'geoengineering' itself to refer solely to solar geoengineering proposals, and in particular stratospheric aerosols injection, ignoring carbon proposals in the definition altogether (see Barrett, 2008). Geoengineering proposals have also been divided along different lines of demarcation, including between those that seek to enhance Earth systems and those that represent 'black-box' engineering (Rayner, 2011).

The emergence of geoengineering as a policy response to climate change has prompted some to reconsider the categorisation of the proposals in context with mitigation options and adaptation. Boucher *et al.* (2013) reflect on the ambiguities of not only geoengineering, but also of mitigation and adaptation, and note a number of overlapping concepts that may confuse policy discourses. They offer five new categories: anthropogenic emissions reductions (AER); territorial or domestic removal of CO_2 and other long-lived greenhouse gases (D-GGR); trans-territorial or trans-boundary removal of CO_2 and other long-lived greenhouse gases (T-GGR); regional to planetary targeted climate or environmental modification (TCM); and adaptation and local targeted climate or environmental modification (CCAM). In a different typology of responses to climate change, Heyward (2013) retains distinctions between mitigation, CDR, SRM, and adaptation, and introduces 'rectification' (compensation) as category of responses for when the others have failed. She adds that *'research and debate [should] cease to be about "geoengineering" and instead focus on the specific features of the proposed technologies, and the appropriate mix of [options]'* (*ibid*: 26), and calls for an abandonment of the term. By contrast, Cairns (2013: 3) argues that the ambiguities of the term offer *'interpretative flexibility for articulating diverse interests within and across contested framings'*.

This section has begun to map out the complex etymology of geoengineering and revealed some of its ambiguities. Indeed this is reflected in the varied public understandings of the term, where just 8% of Americans, British, and Canadians are able to 'correctly' define geoengineering (Mercer *et al.*, 2011). Whilst recognising these ambiguities of geoengineering, for clarity this thesis uses the term to refer to deliberate large-scale interventions in the Earth's climate system in order to moderate climate change; and 'carbon geoengineering' and 'solar geoengineering' to refer to classes of proposals which seek to remove and sequester CO_2 from the atmosphere and to increase the reflection of sunlight back into space, respectively. 'Mitigation' and 'adaptation' are also used to refer to options available to reduce greenhouse gas emissions and reduce the impacts of climate change, respectively.

1.3 Thesis Rationale and Contribution

Appraisals of geoengineering have begun in earnest, with a view to providing vital decision support for policy makers around the world. The rationale for this thesis is rooted in contemporary theoretical perspectives on appraisal design (see Chapter 2) and a critical analysis of those current appraisals of geoengineering (see Chapter 3). The high decision stakes and great systems uncertainties of climate change, and of its intentional manipulation through climate geoengineering over and above that, situate the issue squarely within the realms of 'post-normal science' (Funtowicz & Ravetz, 1992; 1993). This post-normal scientific context, together with further delineations of the uncertainties and incertitude inherent to geoengineering the climate (Wynne, 1992a; Stirling *et al.*, 2007), and a suite of substantive, normative and instrumental imperatives (Fiorino, 1990), compels a particular type of response in appraisal design. It demands the use of methods that do not mischaracterise the issue as one of simple 'risk', but one of 'indeterminate' 'uncertainty', 'ambiguity' or 'ignorance'. It demands the inclusion of 'axiological' (value) perspectives from an 'extended peer community', through wider participation from stakeholders and publics.

In undertaking the first critical analysis of current appraisals of geoengineering, this thesis reveals that the majority of geoengineering appraisals do not adequately respond to the post-normal scientific context of high stakes and uncertainties. The appraisals often mischaracterise the issue as one of 'risk', employing inapplicable 'reductive-aggregative' methods (Stirling *et al.*, 2007) such as risk assessment or cost-benefit analysis. Furthermore, these methods are mostly 'expert-analytic' in nature, exclusively open to experts and excluding wider stakeholders and publics. A significant research gap thus presents itself. Geoengineering proposals should be appraised in a manner that adequately responds the highly uncertain and complex context in which it resides, by adopting a methodology that accounts for indeterminate uncertainty, ambiguity or ignorance and is inclusive to wider stakeholder and public participation as well as experts.

Expert-analytic or 'participatory-deliberative' methods of appraisal are, however, equally susceptible to framings. Framings in appraisal design, conduct and presentation can compel particular outcomes through inadvertent, tacit, or deliberate application of power (Stirling, 2008). The more 'narrow' and the more 'closed' these framings are; for example, through the selection of a limited range and depth of options and criteria; the greater the exercise of power over appraisal outcomes. Such framings can result in 'unitary and prescriptive' recommendations to policy makers that endorse certain courses of action over others, risking entrenchment (Collingridge, 1980), path dependency (David, 2001) and 'lock-in' to particular futures (Arthur, 1989).

Appraisals of geoengineering have often adopted such narrow and closed framings, including a limited range of geoengineering proposals that have been appraised in isolation against a limited range and depth of criteria from a limited range of perspectives. This practice has culminated in the ostensibly high performance of particular proposals, principally stratospheric aerosol injection. Another significant research gap presents itself. Geoengineering proposals should be appraised in a manner that 'broadens out' and 'opens up' to diverse framings, including alternative options, a greater range and depth of criteria, and diverse perspectives, in order to provide 'plural and conditional' recommendations and hedge against premature sociotechnical lock-in (Stirling *et al.*, 2007; Stirling, 2008).

Appraisals of emerging sciences and technologies are increasingly recognised as needing to constitute part of a much wider framework for responsible innovation (Guston & Sarewitz, 2002; Wilsdon & Willis, 2004; Barben *et al.*, 2008; Owen *et al.*, 2013; Stilgoe *et al.*, 2013). These ambitions call for appraisals to be anticipatory in their assessment of the possible impacts of emerging technologies, reflexive in their consideration of individual and institutional framings and interests, inclusive in their involvement of stakeholders and publics as well as experts, and building responsiveness to changing social and technical circumstances in their support for decision and policy making. However, appraisals of geoengineering have not yet adequately taken place under the auspices of such a framework. Whilst some narrowly-framed anticipatory assessments have taken place, critical dimensions of inclusiveness, reflexivity and responsiveness remain unaddressed. One more significant research gap thus presents itself. Geoengineering proposals should be appraised within a broader framework for responsible innovation, espousing anticipatory, reflexive, inclusive and responsive attributes.

This thesis responds to each of these rationales and research gaps through the development of an innovative and participatory appraisal methodology called Deliberative Mapping (DM) that is designed to support the objectives of responsible innovation. For the first time, the method opens up the appraisal of geoengineering to a significant diversity of different framings. From the outset it opens up to a diversity of perspectives, including experts, stakeholders and publics. It opens up the problem definition beyond the narrow frames of current appraisals to one of 'responding to climate change', that introduces a diversity of alternative options spanning mitigation and adaptation. These options are then appraised alongside one another, and in context, against a diversity of participant-defined criteria. The results of this method allow for the relative performance of geoengineering proposals to be explored in comparison with alternative options for tackling climate change for the first time, under these more diverse framings.

The development and application of DM in this context itself presents an interesting opportunity. Whilst building on decades of the successful development and application of DM and its constituent appraisal methods, Multi-Criteria Mapping (MCM) and Stakeholder Decision Analysis (SDA), in the anticipatory appraisal of other analogous emerging sciences and technologies including genetically modified organisms (Stirling & Mayer, 2001); medical transplant technologies

(Davies *et al.*, 2003); and energy technologies (Stirling, 1994; Chilvers & Burgess, 2008), as well as more conventional but complex issues such as managing legacy radioactive waste (Burgess *et al.*, 2004) and forms of environmental planning (Burgess, 2000); the extent to which these other issues can be considered analogous is a critical point for reflection. The issues of focus in this thesis, climate change and geoengineering, are arguably more complex than those aforementioned, contending with far greater spatial and temporal scales.

1.4 Research Themes and Questions

This thesis sets out to address four broad research themes, each comprising two specific research questions, which are detailed below. Taken together, their objective is to 'open up' geoengineering appraisal.

- Research Theme 1: Framing Geoengineering Appraisal

The first research theme relates to a review and critical analysis of the ways in which current appraisals of geoengineering have been framed, with a view to determining the implications these framings may pose for future research.

1. How important are framings in current appraisals of geoengineering and what effect do they have on their capacities to 'broaden out' inputs and 'open up' outputs?
2. What would constitute a suitable methodological response in appraisal design to the limitations of current appraisals of geoengineering?

- Research Theme 2: Specialist Appraisal of Geoengineering

The second research theme relates to an empirical analysis of the ways in which specialists (experts and stakeholders) frame and appraise geoengineering proposals in context with alternative options for tackling climate change.

1. To what extent does diversity amongst experts and stakeholders 'open up' framing of geoengineering appraisal in context with alternative options for tackling climate change?
2. How do geoengineering proposals perform against alternative options for tackling climate change in specialist appraisals?

- Research Theme 3: Public Appraisal of Geoengineering

The third research theme relates to an empirical analysis of the ways in which publics (citizens) frame and appraise geoengineering proposals in context with alternative options for tackling climate change.

1. To what extent does diversity amongst citizens 'open up' framing of geoengineering appraisal in context with alternative options for tackling climate change?
2. How do geoengineering proposals perform against alternative options for tackling climate change in citizen appraisals?

- Research Theme 4: Geoengineering Governance

The fourth and final research theme relates to a synthesis of the ways in which specialists and publics frame and appraise geoengineering proposals in context with alternative options for tackling climate change, with a view to exploring their implications for governance.

1. What are the implications of 'opening up' geoengineering appraisal for governance?
2. How might these implications for governance be implemented under a framework for responsible innovation?

1.5 Thesis Structure and Content

This thesis consists of eight chapters. **Chapter 1** has offered an overview of the state of climate change science and policy in 2013, and an introduction to 'geoengineering' proposals as a new set of policy responses to sit alongside mitigation and adaptation. Whilst interest in geoengineering the climate has gained recent and growing interest, the chapter provides a history of the human desire for climate control that is much older. Its ambiguous definition is then mapped out before the issues involved in geoengineering appraisal are explored and the novel contributions of this research underlined. The chapter closes by outlining four research themes for the thesis and their respective questions, spanning the framing of geoengineering appraisal; the specialist appraisal of geoengineering; the public appraisal of geoengineering; and the governance of geoengineering.

Chapter 2 explores contemporary theoretical perspectives on 'social' appraisal. It begins by reflecting on the 'participatory turn' in science policy from expert-analytic modes of appraisal towards more participatory-deliberative modes, with reference to the rise of the 'risk society', responses to uncertainty and incertitude, and the emergence of post-normal science. It observes the shift in public participation from one of a one-way information deficit towards one of a two-way dialogue, and ultimately 'upstream' engagement. The chapter goes on to examine the propensity for both expert-analytic and participatory-deliberative methods to 'close down' as well as 'open up' under the exertion of power via framings. Diversity and reflexivity are then considered as ways to guard against closure in social appraisal. The chapter then situates social appraisal within a broader framework for responsible innovation so as to promote anticipation, reflexivity, inclusion and responsiveness, before considering particular methods of appraisal that can support this aspiration.

In view of the contemporary theoretical perspectives on social appraisal, **Chapter 3** presents the findings of the first critical analysis of climate geoengineering appraisals. It begins by outlining the method for the systematic review of peer-reviewed and grey literature that underpins the analysis. A review of the main findings of these appraisals is then presented, with particular attention to those that have employed 'participatory-deliberative' methods. A critical analysis is then conducted of the role of framings in shaping appraisal inputs and outputs, and ultimately, epistemic commitments to particular responses to climate change.

In view of the contemporary theoretical perspectives on social appraisal and of the significant and pervasive limitations to appraisals of geoengineering, **Chapter 4** introduces and outlines DM as a theoretically informed methodological response to geoengineering appraisal design. The chapter begins by outlining the rationale for the selection of DM as that response, together with an overview of the DM process and its framing. The methodological design of the specialist strand of the process is then outlined with respect to participant scoping and recruitment, and the conduct of Multi-Criteria Mapping (MCM) interviews. The design of the citizen strand of the process is then outlined with respect to participant scoping and recruitment, an online resource website, and the conduct of citizens' panels and a joint citizen-specialist workshop. The chapter closes by outlining the quantitative and qualitative methods of analysis.

Chapter 5 is the first of two chapters dedicated to the analysis and discussion of the results of the DM process with reference to the wider literature. The results of the specialist strand, composed of experts and stakeholders who participated in the first and second MCM interviews, are presented. The participant-defined 'additional' options are reported, together with the appraisal criteria developed by specialist participants with which to evaluate those options alongside the core and discretionary options. The qualitative performance of different geoengineering proposals, mitigation options and business as usual, is then reported with respect to different groups of criteria. The relative weighted importance of different criteria is then reported together with the overall option rankings.

Chapter 6 is the second of two chapters dedicated to the analysis and discussion of the results of the DM process with reference to the wider literature. The results of the citizen strand, composed of members of the public who participated in the first and second citizens' panels and the joint workshop, are presented. The results of this strand are compared and contrasted throughout this chapter with those of the specialist strand reported in Chapter 5. The chapter begins by examining the ways in which citizens framed the issue and explored the options under consideration. The selected discretionary and citizen-defined 'additional' options are then reported, together with the appraisal criteria developed by citizen participants with which to evaluate those options alongside the core options. The qualitative performance of different geoengineering proposals, mitigation options and business as usual, is then reported with respect to different groups of criteria. The relative weighted importance of different appraisal criteria is then reported together with the overall option rankings for the DM process.

As the penultimate chapter of the thesis, **Chapter 7** presents a synthesis discussion of the DM process' implications for geoengineering governance. Drawing on qualitative data from across both strands of the process, including the previously unexamined process evaluations undertaken by the participants and the specialists' 'foresight' exercise, these implications are discussed on three levels. An evaluation of the DM process itself is undertaken in order to determine its performance and its implications for the conduct of future participatory appraisals and how they relate to governance. An evaluation of how the DM process relates to wider systems of governance is then undertaken to determine its anticipatory, reflexive, inclusive, and responsive contributions towards realising ambitions for broader frameworks of responsible innovation. Four propositions for the governance of geoengineering research and development are then outlined before a consideration of how such recommendations could be implemented as part of a framework for responsible innovation.

As the concluding chapter, **Chapter 8** addresses the research themes and questions set out in this first chapter and presents conclusions and key insights from across the thesis. The chapter begins by addressing those research questions relating to the framing of geoengineering appraisal, within both current appraisals and in the DM process. Those research questions relating to the appraisal of geoengineering by specialists and citizens are then addressed together, reflecting on the substantive performance of different geoengineering proposals and of their alternatives, and on the implications of these findings for policies on tackling climate change. Those research questions concerning the governance of geoengineering are then addressed, reflecting on the propositions for governance and the implications for policy in practice. The thesis then concludes by discussing its limitations in the context of challenges and questions for future research, and by summarising its substantive contributions to the academic and policy literatures.

Chapters 1, 3, 4 and 5 comprise parts of this thesis that have been researched, written and published by the author in edited form in the academic journals *WIREs Climate Change* (Chapters 1 and 3) and *Global Environmental Change* (Chapters 4 and 5) and in an opinion article for the forthcoming *Earthscan* volume *Geoengineering Our Climate: Ethics, Politics and Governance* (Chapter 3). One further article is currently under review with *Public Understanding of Science*, which comprises parts of Chapters 4 and 6 of this thesis. Dr. Jason Chilvers, Dr. Naomi Vaughan and Professor Tim Lenton appear as co-authors through their provision of supervisory support. Citations for these publications are as follows:

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Chapter 2

Theoretical Perspectives on Social Appraisal

This chapter outlines the theoretical basis for 'opening up' social appraisal in complex and uncertain risk issues, including to wider stakeholder and public participation and as part of broader ambitions for responsible innovation. In doing so, this thesis adopts constructivism as its epistemological point of departure in approaching science, knowledge and nature. The construction metaphor here refers to the artifactual constructivism espoused by Latour (1987) and Haraway (1992), where its principal tenets describe: *'The reality of the objects of scientific knowledge [as] the contingent outcome of social negotiation among heterogeneous human and non-human actors'* and *'Ultimate truth [as] undecidable'* (Demeritt, 1998: 176). The foundation of this epistemological perspective lies with an ontology where *'No absolute ontological distinction [can be made] between representation and reality, nature and society'* (*ibid*: 176).

Section 2.1 outlines the 'participatory turn' in science policy from expert-analytic modes of appraisal towards more participatory-deliberative modes, with reference to the rise of the 'risk society', responding to uncertainty and incertitude, and the emergence of post-normal science. It then observes the shift in public participation from one of a one-way information deficit, public understanding of science, to one of two-way dialogue, and ultimately 'upstream' engagement. Section 2.2 then examines the propensity for both expert-analytic and participatory-deliberative to 'close down' as well as 'open up' under the exertion of power and framings. It then explores diversity and reflexivity as ways to overcome closure in social appraisal. Section 2.3 then situates social appraisal within a broader framework for responsible innovation so as to promote anticipation, reflexivity, inclusion and responsiveness. The chapter concludes by summarising these perspectives on social appraisal with a view to reviewing the current social appraisal of climate geoengineering proposals in the next chapter.

2.1 The 'Participatory Turn' in Science Policy

In this section the origins and expressions of the 'participatory turn' in science policy will be explored in four subsections. First, the prevailing technocratic linear model of science policy will be explored as an artefact of the 'risk society', before a discussion of its limitations under the emergence of 'post-normal science', in Section 2.1.1. Second, understandings of uncertainty and incertitude are delineated as part of other substantive, normative and instrumental reasons for public participation in decision making on science policy in Section 2.1.2. Third, the emergence of a new participatory model will be documented, from the development and abandonment of a deficit model of science communication to the recognised need for genuine dialogue in Section 2.1.3. Fourth, contesting definitions of 'participation' itself are examined as a reason for limited success, before calls for 'upstream' engagement with emergent sciences and technologies are outlined in Section 2.1.4.

2.1.1 Science in the risk society

The etymology of 'risk' can be traced back to the mid-Seventeenth Century with the French *risqué*, which itself derives from the Italian *risco* ('danger') (OED, 2008). The term has since come to pervade modern society, so that it has come to be a defining feature of post-industrial modernity; a society organised in response to risks: 'the risk society'. Giddens (1999) asserts that such a society is not one that is necessarily more hazardous than those in the past, but one that has emerged from fears abounding the end of nature and tradition, fostering an increasing *'preoccup[ation] with the future (and also with safety)'* (*ibid*: 3). On the other hand, Beck (1992) asserts that the risk society is a product of reflexive modernisation: *'a systematic way of dealing with hazards and insecurities induced and introduced by modernisation itself'* (*ibid*: 21). Nevertheless, the risks of contemporary industrial society, Beck argues, including anthropogenic climate change, have come to be characteristically imperceptible except through expert scientific analysis.

The authority and systems of accountability offered by the natural sciences in detecting the risks of contemporary society have contributed to a prevalence of institutionalised 'scientism' in modern politics and society (Ezrahi, 1990). This invariably positivist view of science as the most authoritative form of inquiry has perhaps inevitably led to a linear model or 'technocracy' of science and politics, where science advice is presumed to be de-politicised and intended to precede and compel political decision making: 'science speaks truth to power' (Jasanoff, 1990). This linear model upholds two central ideals: administrative rationalism ('leave it to the experts') and economic rationalism ('leave it to the market') (Dryzek, 2005). Each of these ideals bestows primacy to ostensibly 'objective' scientific knowledge and instrumental forms of rationality. Involving policy makers, administrators and scientists or businesses and economists, they preclude broader stakeholder and public participation in decision making.

The linear model of science policy is supported by expert advisory committees, regulatory instruments and other governmental agency and technical decision support tools. These tools most often take the form of appraisal methods, including (but not limited to) risk assessment, cost-benefit analysis (CBA) and environmental impact assessment (EIA). Such 'reductive-aggregative' expert-analytic methods (Stirling *et al.*, 2007) can be considered to address what Kuhn (1962) called issues for 'normal' science. This 'puzzle-solving' science asserts that the understanding and control of risk can be achieved through the reduction of uncertainty by the appliance of more accurate and precise scientific knowledge. It is characterised by a state where *'uncertainties are managed automatically, values are unspoken, and foundational problems unheard of'* (Funtowicz & Ravetz, 1993: 740). However, in risk issues where *'facts are uncertain, values are in dispute, stakes [are] high and decisions [are] urgent'* (*ibid*: 744) these technical problem-solving strategies can no longer be considered appropriate. Funtowicz & Ravetz (1992; 1993) define such issues as those pertaining to 'post-normal' science.

Showing the interactions between the different scales of systems uncertainties and sizes of decision stakes, Funtowicz & Ravetz (1992; 1993) outline three tiers of problem-solving strategy for responding to risks (see Figure 2.1). The first, and most familiar, strategy is that of applied science. Where systems uncertainties and decision stakes are at their lowest, this strategy can be considered as 'basic' science where uncertainty can be managed at a technical level whilst there are no external interests to its function. Applied science opens up this function to external interests, which are included in an extended peer research community. The second strategy is that of professional consultancy, where uncertainty is more complex and cannot be managed at a technical level, but rather at a methodological level. This strategy may transcend simple client purposes and experience conflicting purposes between different stakeholders who make up a further 'extended peer community'.

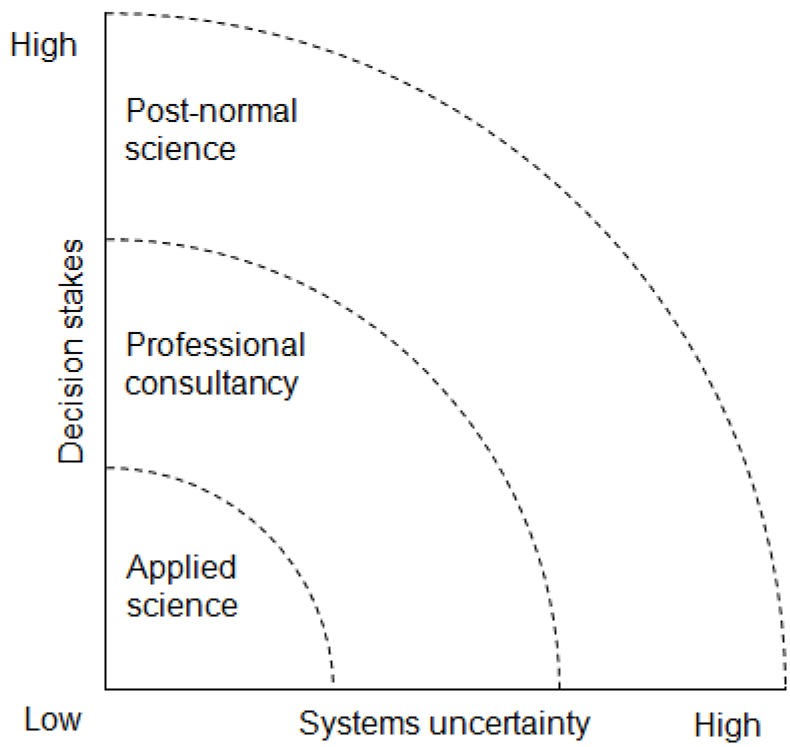


Figure 2.1. Problem-solving strategies (redrawn from Funtowicz & Ravetz, 1993: 745).

The third strategy is that of post-normal science itself, where systems uncertainties and decision stakes are both high. At this level, uncertainty is of an epistemological sort, whilst decision stakes represent an increasing conflict of purposes. According to Funtowicz & Ravetz (1993), *'any of the problems of major technological hazards or large-scale pollution belong to this class'* (*ibid*: 750). It is thus clear from its high systems uncertainties and decision stakes that the global environmental issue of anthropogenic climate change is one of post-normal science. Moreover, it is clear that the prospect of deliberately geoengineering the Earth's climate, over and above the inadvertent climatic forcing as a result of industrial society, is situated squarely within the sphere of post-normal science. In decision contexts characterised by post-normal science it is imperative that axiological factors (values) are included from an extended peer community of all stakeholders and publics with an interest in the issue. In the intra- and inter-generational cases of global climate change and prospective geoengineering this is no small challenge.

2.1.2 Uncertainty and participation

Post-normal science has repositioned uncertainty as a central concept in scientific methodology. However, where Funtowicz and Ravetz posit that uncertainty can be viewed on an objective scale from low to high, others have partitioned the concept into different aspects. Wynne (1992a) asserts that uncertainty can be considered in four different kinds: risk, uncertainty, ignorance and indeterminacy (see Figure 2.2). Whilst risk, uncertainty and ignorance, can broadly be considered to correspond to the technical, methodological and epistemological uncertainties considered by Funtowicz and Ravetz, indeterminacy introduces an important new dimension regarding issue definition. Under indeterminacy, Wynne questions whether knowledge is:

> *'adapted to fit the mismatched realities of application situations, or whether those (technical and social) situations are reshaped to 'validate' the knowledge'* (*ibid*: 115).

Rather than merely a greater form of uncertainty, indeterminacy is argued to permeate each tier of uncertainty and problem-solving strategy and is expressed as a function of the (also indeterminate) decision stakes, or contingent social commitments. With respect to the issues of climate change and geoengineering then, it is clear that it is not one of risk, but of indeterminate uncertainty and ignorance. Furthering the call for an extended peer community espoused under post-normal science, Wynne calls for new 'regulatory' cultures that encourage public participation to address the conditional social commitments of scientific knowledge.

> *Risk*: '[We] know the odds'.
>
> *Uncertainty*: '[We] don't know the odds. May know the main parameters. May reduce uncertainty but increase ignorance'.
>
> *Ignorance*: '[We] don't know what we don't know. Ignorance increases with increased commitments based on given knowledge'.
>
> *Indeterminacy*: 'Causal chains or networks open'.

Figure 2.2. Four different kinds of uncertainty (from Wynne, 1992a: 114)**.**

In delineating uncertainty further still it can be considered as the emergent property of incomplete knowledge, or incertitude, which bears particular significance for appraisal design. Stirling (1999; 2003) shows four possible states of incertitude in showing the relational interactions between knowledge about probabilities and outcomes: risk, uncertainty, ambiguity and ignorance (see Figure 2.3). Whilst risk, uncertainty and ignorance can broadly be considered to correspond to those uncertainties of the same name under Wynne (1992a), ambiguity introduces an important new dimension where probabilities are not problematic but disagreements may exist as to the definition or understanding of possible outcomes: 'contradictory certainties' (Thompson & Warburton, 1985). The incertitude of ambiguity is thus added to the mix of indeterminate uncertainties that pervade the issues of climate change and geoengineering. Stirling *et al.* (2007) argue for a humble and dynamic approach to incertitude alongside the inclusion of diverse knowledges to address social framings, including public participation, as part of a wider broadening out of appraisal to which we return in Section 2.2.3.

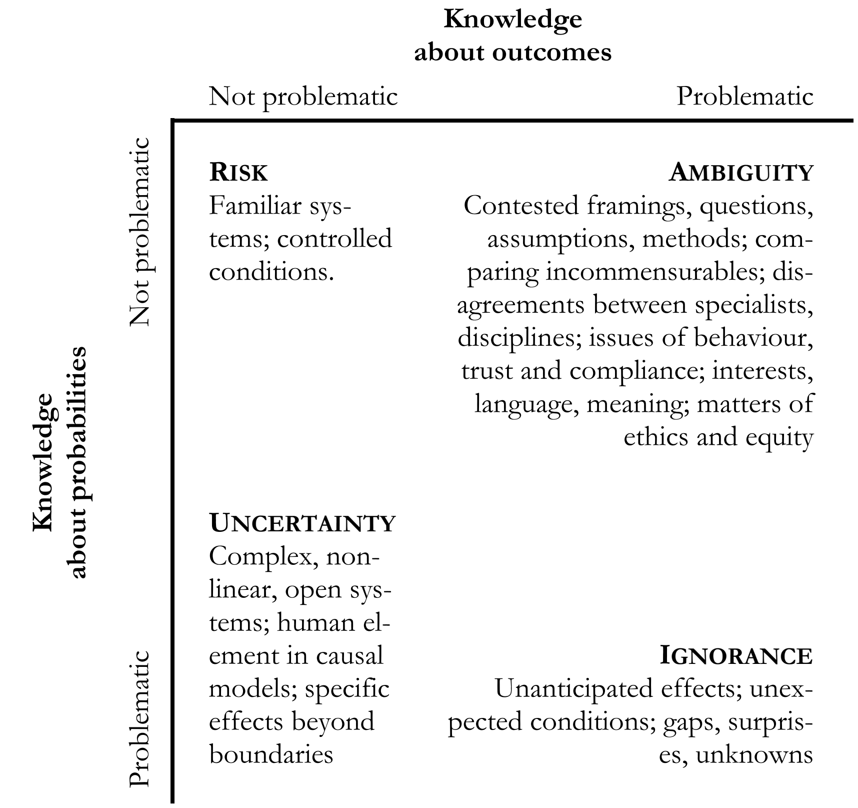


Figure 2.3. Four states of incertitude with schematic examples (redrawn from Stirling *et al.*, 2007: 9).

The implications of the emergence of post-normal science and radical uncertainties show us that the technical 'reductive-aggregative' appraisal methods at the disposal of linear model of science policy treat all uncertainties as 'risk' issues that can be understood and reduced through the appliance of greater precision. Such application may at best reduce 'uncertainty' in its narrower sense, but may also increase 'ignorance' and neglect 'indeterminacy' in both the system and its social actors (Wynne, 1992a). Indeed, the situation of climate change and geoengineering within the sphere of post-normal science and within the uncertain, ambiguous and even ignorant kinds of uncertainty and states of incertitude compels a particular suite of responses in appraisal design. The methods that pertain to issues of 'risk' (e.g. decision analysis, statistical errors) are no longer applicable. More precautionary methods are demanded under 'uncertainty' (e.g. decision heuristics, sensitivity analysis), ambiguity (e.g. participatory deliberation, Multi-Criteria Mapping), and ignorance (e.g. horizon scanning, transdisciplinarity) (Stirling, 2007a). Importantly, it is clear that in order to address such issues public participation is needed to include axiological factors from an extended peer community to address the social commitments and framings of scientific knowledge.

The rationale for public participation in complex and uncertain issues extends beyond post-normal science and an appreciation of uncertainty and incertitude. Fiorino (1990) outlines three powerful arguments in favour of public participation. The first, a substantive argument, is that citizen's lay judgements of risk are also valid, and in some cases demonstrate a higher sensitivity to social and political values than those of experts. Citizen's local knowledge is contextual, constructed through bricolage, and continually evolving, thereby potentially contributing to the 'social intelligence' of any decision making (Irwin, 1995). Indeed, following the radioactive fallout from the Chernobyl nuclear disaster in 1986, ill-informed livestock movement and sale restrictions were enforced in Cumbria after a failure to consult the local soil knowledge of sheep farmers (Wynne, 1996). The second argument by Fiorino, a normative one, is that the current technocratic approach is contradictory to the ideals of democracy, and that ethically *'citizens are the best judge of their own interests'* (Fiorino, 1990: 227). The third argument, an instrumental one, is that citizen participation makes decisions more legitimate, enhancing transparency and trust and reducing the likelihood of decision errors.

2.1.3 From deficit to dialogue

The technocratic linear model of science policy, supported by technical, reductive-aggregative expert-analytic appraisal methods, has been exposed for its deficiencies in recent decades. As the production and uses of sciences and technologies began to increasingly transcend the historically discrete boundaries between academia, business and politics in the late Twentieth Century, the public started to question science as motivated purely by inquiry (Wilsdon & Willis, 2004). A number of high-profile public controversies involving science policy have since emerged alongside a 'crisis of trust' (e.g. Touraine, 1995), including those surrounding nuclear energy in the 1980s and Bovine Spongiform Encephalopathy (BSE); Measles, Mumps and Rubella (MMR) vaccines; and genetically modified (GM) crops in the 1990s. It soon became clear that public participation would be necessary to counter such attitudes.

Despite the apparent shortcomings of the linear model, the legacy of scientism persisted and a resonant model of science communication was developed. In 1985 the Royal Society, under the chairmanship of Walter Bodmer, published a watershed report entitled 'The Public Understanding of Science' (Royal Society, 1985). Drawing on analytic interpretations of risk perception from the field of cognitive psychology, the resultant model of science communication centred upon the belief that unfavourable attitudes toward science and technology had arisen through a lack of 'rational' understanding or ignorance of scientific facts and evidence. Branded the cognitive 'deficit' model by Science and Technology Studies (STS) scholars (e.g. Wynne, 1991), the approach assumed that upon improving scientific literacy through one-way science dissemination, the public would be persuaded to view science and technology more favourably.

Whilst it has been argued that there is some evidence for a correlation between accurate scientific knowledge and favourability of attitude towards science (e.g. Bauer *et al.*, 1994), it is questionably weak (e.g. Evans & Durant, 1995). Moreover, with 'morally contentious' sciences, as might be presumed for geoengineering, attitudes can often become more sceptical with increasingly accurate scientific knowledge (*ibid*, 1995). The deficit model has since attracted much instrumental and epistemological criticism. Wynne (1992b) has argued that the deficit models' quantitative measures of understanding fail to capture the full range of relevant knowledge domains, ignoring forms of institutional embedding, patronage, organisation and control of sciences and technologies. Thus the model neglects the contextualisation of scientific knowledge by other knowledges in any given circumstance (Sturgis & Allum, 2004). For example, knowledge of the institutional arrangements which grant the authority of scientific expertise is one such context in which public trust of experts can be influenced (Yearley, 2000).

Further epistemological critique comes from a social constructivist perspective. In upholding the analytic interpretation of risk perception with its 'objective' and 'rational' views of attitude construction the deficit model neglects the role of people's values and ontological beliefs or worldviews in the formation of perceptions (Slovic & Peters, 1998). In recognising these critically different influences on perception, the Cultural Theory of Risk offers an enlightened way of understanding attitude formation without removing people from their social and cultural settings (Douglas, 1970; Douglas & Wildavsky, 1982; Thompson *et al.*, 1990). The theory examines how shared values and beliefs, or cultural biases, interact with interpersonal social relations to construct viable worldviews, or 'ways of life': hierarchism, individualism, egalitarianism, fatalism and autonomy. Cultural Theory's four primary ways of life (exclusive of autonomy) can be mapped upon a 'grid-group' typology, which captures the extent to which an individual's life is prescribed by social regulation and social contact. Despite an apparent asymmetry in its treatment of these ways of life (Stirling, 1998a), they provide a valuable insight into why different people and cultures perceive risks, and their alternate resolutions, differently.

Following such criticism it since became clear that a new model of public participation, and of science policy more widely, was needed. Fischhoff (1995) captured its progressive evolution in seven stages of risk communication, marking the transition from the linear model and its expert-analytic methods of appraisal, through different developments of the deficit model, and culminating in partnership (see Figure 2.4). By 2000, the UK House of Lords responded and recognised 'a new mood for dialogue' (HoL SCST, 2000), casting out the Public Understanding of Science approach and its deficit model. This new model is one that draws upon the ideals of what Dryzek (2005) calls democratic pragmatism ('leave it to the people'). Rather than operating a 'decide-announce-defend' procedure involving only policy makers and experts, such a system also involves publics and stakeholders and the diverse knowledges they possess through a 'meet-understand-manage' procedure. The idea of democratic pragmatism marks the normative transition from 'government' to 'governance': from state centred decision making to enabling the participation of a far broader range of actors.

1. All we have to do is get the numbers right
2. All we have to do is tell them the numbers
3. All we have to do is explain what we mean by the numbers
4. All we have to do is show them that they've accepted similar risks in the past
5. All we have to do is show them that it's a good deal for them
6. All we have to do is treat them nice
7. All we have to do is make them partners

Figure 2.4. Seven stages of evolution in risk communication (from Fischhoff, 1995: 138)**.**

2.1.4 Moving participation 'upstream'

In reflecting on public 'participation' itself, Renn *et al.* (1995) provide an accepted definition:

> *'[F]orums for exchange that are organised for the purpose of facilitating communication between government, citizens, stakeholders, interest groups, and businesses regarding a specific decision or problem'* (*ibid*: 2).

Participation can, however, be defined and interpreted in different ways and at different levels. Indeed, its different and often vague definitions have arguably assisted the idea in gaining momentum in policy discourses, but concurrently may also have contributed to shortcomings in practically delivering its democratising promises (Cornwall, 2008). Notably, despite criticisms of the deficit model and progressive sentiments towards dialogue, the newly sought model has often proved elusive. Indeed, *'public deficit explanations of 'mistrust' have actually been continually reinvented'* (Wynne, 2006: 211) where *'no sooner have 'deficit' models of the public been discarded than they reappear'* (Wilsdon *et al.*, 2005: 19).

Arnstein's (1969) 'ladder of citizen participation' remains one of the most influential of these competing definitions. The first of three levels in the ladder, 'nonparticipation', outlines 'manipulation' and 'therapy' which seek to educate or cure participants. The second level, 'degrees of tokenism', outlines 'informing', 'consultation' and 'placation' which seek to allow participants to hear and be heard, but not to decide. The third and highest level, 'degrees of citizen power', outlines 'partnership', 'delegated power' and 'citizen control', which seek to enable increasing degrees of citizen decision-making power. Partnership enables participants to negotiate with the conventional decision makers, whilst delegated power and citizen control enable participants to hold the majority of, or total, decision making power.

Other typologies have evolved since Arnstein's ladder and explored the idea from different perspectives. From the perspective of users and practitioners, for example, Pretty (1995) introduces an equally normative but different 'ladder' ranging from 'manipulative participation' through to 'self-mobilisation'. Others still have attempted to synthesise the two perspectives (citizens and users) and developed a more refined typology consisting of four levels of participation: nominal, instrumental, representative and transformative (White, 1996). More recently, levels of participation have been defined by their differing communicative strategies. These levels comprise education and information provision; information provision and feedback; involvement and consultation; and extended involvement (e.g. Wilcox, 1994; Petts & Leach, 2000). Each of these levels maps onto three different decision making styles: i) informing about already made decisions; ii) listening and learning for contributing to a decision; and iii) exchanging views to make a collaborative decision (DETR, 1998). This equates to three aggregated levels of participation and associated methods: i) education and information provision; ii) consultation; and iii) deliberation / dialogue (Chilvers *et al.*, 2003).

Policy pressures for including citizen participation in environmental decision making have rapidly increased, with several high profile developments including the Rio Declaration (UNDESA, 1992) and Agenda 21 (UNCED, 1992), the Aarhus Convention (UNECE, 1998), and more recently, calls for 'upstream engagement' (Wilsdon & Willis, 2004). What has followed is the steady development of new participatory and dialogue-focussed forms of citizen engagement with emergent sciences and technologies. Despite this a disconnect remains between these dialogues and the ability of the public to influence the *'choices, priorities and everyday practices of science'* (Wilsdon & Willis, 2004: 18). Depending on how dialogue is framed and used, such engagement can focus only upon certain questions presented at certain phases during research and development. This ignores deeper questions about the values, vested interests and 'imaginaries' guiding research and development processes, risking limited public influence over developmental trajectories (Macnaghten *et al.*, 2005).

Following these concerns there has been increasing interest in the notion of 'upstream' engagement, or engaging with publics before significant research and development into a particular science or technology has taken place, so that *'it can inform key decisions about their development and before* *deeply entrenched or polarised positions appear'* (Royal Society and Royal Academy of Engineering, 2004: xi). However, the idea of upstream engagement is a deceptively simple one which in reality is contested in both concept and practice (Rogers-Hayden & Pidgeon, 2007). Even the metaphor 'upstream' itself has been considered as 'unhelpful' given its implicit linear and deterministic suggestion of a certain direction of flow (Stirling, 2008). Whilst acknowledging the difficulties in defining upstream engagement, Rogers-Hayden & Pidgeon (2007: 346) offer a working definition:

> *'Dialogue and deliberation amongst affected parties about a potentially controversial technological issue at an early stage of the research and development process and in advance of significant applications or social controversy'.*

Much as with the different forms of uncertainty and incertitude discussed in Section 2.1.2, the need for upstream engagement on geoengineering with public participation compels a particular suite of responses in appraisal design (see POST, 2001; Wilsdon & Willis, 2004). These include deliberative participatory methods of different scales, including (but not limited to) focus groups, citizens panel's, consensus conferences, and Deliberative Mapping. One critical feature of upstream engagement is the need to open up debate, the issue to which we now turn in Section 2.2.

2.2 'Closing Down' and 'Opening Up' Social Appraisal

In this section the dichotomy between established and exclusive expert-analytic methods of appraisal and newer and inclusive participatory-deliberative methods is re-examined with attention to power. Power is a central commonality between both approaches, and is explored in terms of its exertion through framings in appraisal design in Section 2.2.1. The concepts of diversity and reflexivity are then introduced in Section 2.2.2 as means of managing such power.

2.2.1 Power and framing in 'social' appraisal

The process of appraisal, of informing (as distinct to forming) decision making and broader institutional commitments to technology, is inherently 'social' (Smith & Stirling, 2007; Stirling *et al.*, 2007). Social processes condition both the inputs to and outputs from appraisals through the dynamic sociotechnical systems in which subjects reside (Scoones *et al.*, 2007) and the governance processes in which appraisals are embedded and constituted (Leach *et al.*, 2007). These conditioning processes represent applications of power ('the exercise by one group of social actors of influence, control, authority, command or dominion over others') that often manifest in appraisal design (Stirling, 2008: 274). Power dynamics operate in different ways in different fields of study (Bourdieu, 1996) and are often ambiguous with respect to their intentionality (Foucault, 1980). The application of power is therefore not necessarily deliberate or even explicit, but may be inadvertent or tacit and implicit.

The notion of power dynamics in appraisal applies equally to expert-analytic methods and to participatory-deliberative methods alike, even if it is in different ways (Stirling, 2005). It is well established that these power dynamics are articulated through 'framings': the ways in which social actors choose to organise and communicate ideas (Goffman, 1974; Wynne, 1987; Jasanoff, 1990). These framings include the ways in which problems in question are defined; options and their alternatives are chosen; methods are selected, processes are designed; and issues prioritised (see Figure 2.5 for these and a selection of other factors influencing framings). Other framings may bear more relevance to one approach more than the other. For example, the handling of uncertainties and the constitution of proof are more relevant to expert-analytic approaches, whilst the style of facilitation and stakeholder identification are more relevant to participatory-deliberative methods. Such framings are highly contestable for their inherent subjectivities: in the motivations for their use, the ways in which they are used, and the ways in which their outputs are interpreted.

Equally relevant to both expert-analytic and participatory-deliberative approaches:

- Setting of agendas
- Prioritisation of issues
- Power relations
- Treatment of dissensus
- Defining problems
- Deciding on context
- Definition of options
- Design of process
- Posing of questions
- Choice of methods
- Selection of alternatives
- Drawing boundaries

More relevant to expert-analytic approaches:

- Discounting of time
- Setting of baselines
- Handling uncertainties
- Constituting proof
- Formulating criteria
- Basis for probabilities
- Recruiting of expertise
- Exploring sensitivities
- Characterising metrics
- Including disciplines
- Research commission
- Interpreting results

More relevant to participatory-deliberative approaches:

- Stakeholder identifying
- Participant recruitment
- Protagonist personality
- Findings documentation
- Phrasing of questions
- Information provision
- Medium of discourse
- Dynamics of persuasion
- Bounding of remits
- Choice of focus
- Style of facilitation
- Adoption of norms

Figure 2.5. A selection of factors influencing the framing of appraisal (from Stirling *et al.*, 2007: 17).

Through such framings, inputs to appraisal designs may act to condition their outputs. In particular, it is when these inputs are 'narrow' in their design that framing can most significantly influence outputs. The selection of a narrow range of options for addressing a narrowly defined problem, for instance, will inevitably yield an output that perhaps excludes equally legitimate, alternative options. The '2020 Vision' plan for agriculture and livelihoods in India presents a useful illustration of such a framing (Mehta, 2005; Stirling *et al.*, 2007). The problem definition adopted for a citizens' jury process as part of the plan's engagement strategy centred on developing competitive and commercial agriculture, where genetically modified (GM) crops featured as the dominant option. As many local stakeholders and non-governmental organisations later proceeded to observe, such a framing overlooked other, perhaps more desirable definitions of the 'problem' in question and other, perhaps more desirable options for responding to it.

Power through framing thus presents challenges for both expert-analytic and participatory-deliberative approaches. Indeed, this is a particularly significant issue for the latter suite of methods, which often seek to guard against power as part of their normative aims. Equally, both approaches are also capable of the concealment and reification of, or the 'closed' treatment of, these sensitivities in appraisal output presentation. Taken together, narrow inputs to appraisal and closed outputs from appraisal amount to a *'closing down [of] wider policy discourses on science and technology choice'* (Stirling, 2008: 278). These powers of framing can represent forms of 'decision justification' (Collingridge, 1980), whether they are 'weak' in seeking that a decision be made or 'strong' in seeking that a particular decision, or 'commitment' be made (Stirling, 2008). Ultimately, these justification pathways culminate in so-called 'unitary and prescriptive' policy advice that presents a single or small range of decision options that are ostensibly preferable given those framings that are privileged (*ibid*).

2.2.2 Diversity and reflexivity

'Closing down' on particular choices through narrowly-framed inputs and their concealment in appraisal outputs can appear to produce authoritative and unambiguous policy recommendations (Stirling, 2008). However, this approach to decision support in both expert-analytic and participatory-deliberative methods neglects the inherent scopes for social agency and indeterminacy, leading to less transparent, accountable and robust decisions. By contrast, the notion of 'opening up' choice seeks to 'broaden out' appraisal inputs to a diversity of alternate framings to account for different problem definitions, options, perspectives, criteria, and so on. Similarly, it seeks to 'open up' appraisal outputs to reflection on those framings, or 'reflexivity'. Instead of the unitary and prescriptive policy recommendations that a closing down approach to appraisal bring, opening up thus yields 'plural and conditional' recommendations that expose sensitivities to framing. Whilst these recommendations may appear more ambiguous, they are transparent, accountable, and collectively far more robust (Stirling, 2003).

The capacities for appraisals to narrow in or broaden out and close down or open up can be discussed as four possible and ideal permutations in appraisal design and presentation: 'narrow and closed', 'narrow but open', 'broad but closed and 'broad and open' (Stirling *et al.*, 2007) (see Table 2.1). Arguments for pursuing this latter permutation, especially in decision contexts of high uncertainty and complexity such as climate change geoengineering, pose specific implications for the design of both expert-analytic and participatory-deliberative appraisal methods. In expert-analytic methods, rather than employing the sorts of reductive-aggregative approach discussed earlier in Section 2.1, they will instead pay particular attention to the implications of different framings and draw on procedures such as sensitivity analysis (Saltelli, 2002) or scenario analysis (Werner, 2004). Multi-Criteria Mapping (MCM) is one expert-analytic method that has been explicitly designed to respond to issues of narrowness and closure (Stirling & Mayer, 2001). In a significant development of multi-criteria decision analysis (Dodgson *et al.*, 2001), the process adopts a heuristic framework to allow participants to define options and criteria, score option performance and apply criteria weightings, whilst also eliciting essential qualitative reasoning and qualifications. The result is a 'map' of the diverse ways in which different alternative options can be framed.

Table 2.1. Permutations of breadth and openness in appraisal (redrawn from Stirling *et al.*, 2007).

Permutation	Example
'Narrow and closed' appraisal	A cost-benefit analysis focuses on ranking options in terms of monetary externalities, or a selectively recruited participatory process delivers single prescriptions.
'Narrow but open' appraisal	A risk assessment is conveyed to policy makers using full sensitivity analyses, or a stakeholder deliberation explores a range of visions and scenarios.
'Broad but closed' appraisal	A well-resourced, broadly constituted participatory appraisal, including multiple contending expert and stakeholder witnesses, aims at producing consensus prescriptions for policy.
'Broad and open' appraisal	An inclusive participatory appraisal, with deep expert and stakeholder engagement, that focuses on uncertainties and provides for high transparency over the implications of dissenting views.

In participatory-deliberative methods, rather than seeking a narrowing and closing consensus between participants, they will instead seek to map a pluralistic discourse that accounts for the diversity of perspectives that bear on any given issue (Rescher, 1993). Plurality, however, does not necessarily preclude the possibility for consensus (Dryzek & Niemeyer, 2006). Indeed, one such participatory-deliberative method, Deliberative Mapping (DM), has sought to map divergence of perspectives and revealed areas of consensus (Burgess *et al.*, 2007). In its first trial, mapping divergent perspectives on options for addressing the 'kidney gap' in UK medical transplant services, a considerable degree of consensus emerged between different groups of participants over the performance of particular options (Davies *et al.*, 2003). Such consensus is more robust for its basis in a process that seeks to map diversity, rather than seeking to narrow and prescribe decisions. DM is quite different, however, to other methods of appraisal. It is what can be called a hybrid 'analytic-deliberative' method. It brings together elements of both expert-analytic methodology and of participatory-deliberative methodology to include experts as well as stakeholders and publics to reconcile the need for analytic-deliberative integration (Stern & Fineberg, 1996).

It is clear then that in seeking to proffer plural and conditional policy advice and recommendations, methods of appraisal should seek to both broaden out inputs and open up outputs, rather than narrowing in inputs and closing down outputs. Stirling *et al.* (2007) offer a schematic space for examining the extent to which methods of appraisal narrow or broaden and close or open option choice (see Figure 2.6). In seeking to appraise geoengineering, methods in the lower right-hand quadrant of the figure are thus most desirable, with those in the upper left-hand quadrant being the least desirable.

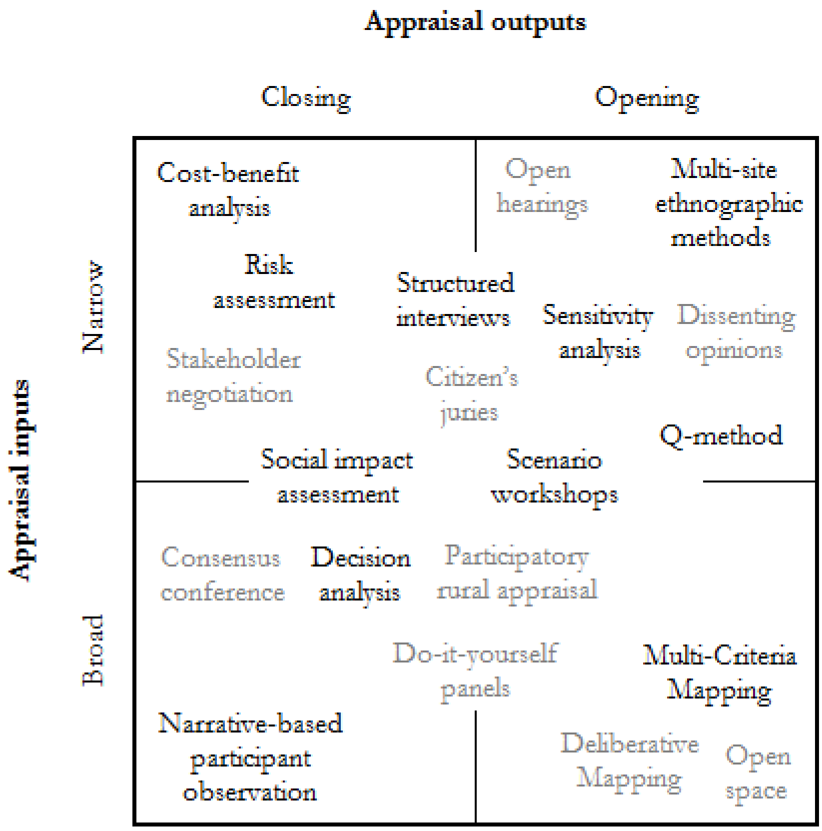


Figure 2.6. A schematic space for examining individual methods in appraisal design (redrawn from Stirling *et al.*, 2007). Methods in black text indicate expert-analytic methods and those in grey text indicate participatory-deliberative methods (note that Deliberative Mapping is an analytic-deliberative hybrid that integrates elements of expert-analytic and participatory-deliberative methodology).

2.3 Social Appraisal as Part of Responsible Innovation

In this section social appraisal is situated within broader ambitions for 'responsible innovation'. The term responsible (research) and innovation emerged relatively recently, during the early years of the Twenty-First Century (Hellstrom, 2003; Guston, 2004), but has a longer history in 'responsible development' (Fisher & Rip, 2013) and the ethical, legal and social implications of emerging areas of science and technology (Owen *et al.*, 2012). In seeking to bring together disparate definitions of the term, Stilgoe *et al.* (2013: 1570) offer a broad definition: *'responsible innovation means taking care of the future through collective stewardship of science and innovation in the present'*. This orientation around the future draws heavily on the concept of 'anticipatory governance', the term of which itself can also be traced back to the early years of the Twenty-First Century (Karinen & Guston, 2010).

Anticipatory governance is defined as *'a broad-based capacity extended through society that can act on a variety of inputs to manage emerging knowledge-based technologies while such management is still possible'* (Guston, 2008: vi). The concept marks a response to Collingridge's (1980) 'technology control dilemma', in which governance architecture cannot know the impacts of an emerging technology until significant development has taken place; by which time governance could not exercise adaptiveness over the trajectories of its innovation. Under such circumstances, innovation may become path dependent (David, 2001), and 'locked-in' (Arthur, 1989) to society, risking public controversy. Anticipatory governance argues that this dilemma can be mitigated through various forms of reflexivity, or reflection, on: foresight of possible futures, engagement with broader stakeholders and publics, integration of disciplines, and their collective production ensemble (Barben *et al.*, 2008). Real-time technology assessment is one such method for building reflective capacity as part of innovation (Guston & Sarewitz, 2002).

In developing a framework for responsible innovation from the disparate concepts and practices in this emerging field, Owen *et al.* (2013) outline four central dimensions of responsible innovation: anticipation, reflexivity, inclusion and responsiveness. These dimensions have emerged from an expansive analysis of public concerns and questions raised across 17 UK public dialogues on science and technology (Macnaghten & Chilvers, 2013). Indeed, this analysis included consideration of an early public dialogue on geoengineering: Experiment Earth (NERC, 2010), where upstream questions and concerns relating to controllability, reversibility, naturalness, fairness and equity were raised. Figure 2.7 organises questions from their analysis around those concerning the products, processes and purposes of innovation.

Product questions:

- How will the risks and benefits be distributed?
- What other impacts can we anticipate?
- How might these change in the future?
- What don't we know about?
- What might we never know about?

Process questions:

- How should standards be drawn up and applied?
- How should risks and benefits be defined and measured?
- Who is in control?
- Who is taking part?
- Who will take responsibility if things go wrong?
- How do we know we are right?

Purpose questions:

- Why are researchers doing it?
- Are these motivations transparent and in the public interest?
- Who will benefit?
- What are they going to gain?
- What are the alternatives?

Figure 2.7. Lines of questioning on responsible innovation (from Stilgoe *et al.*, 2013: 1570; Macnaghten & Chilvers, 2013).

The first dimension of responsible innovation is that of anticipation (Owen *et al.*, 2013). Anticipation, as distinct to 'prediction', refers to the possible impacts that an emerging technology might bring, be they positive or negative. It encourages innovators to ask 'what if…?' questions that relate to the known, the unknown and the possible (Ravetz, 1997). The dimension of anticipation draws on the concept of foresight that is fundamental to anticipatory governance, focusing on exploration of sociotechnical 'imaginaries' of the future (Sarewitz, 1996). In turn, this foresight can be used to avoid undesirable futures and shape more desirable futures; allocating resources appropriately (te Kulve & Rip, 2011). In addition to real-time technology assessment, methods that support upstream engagement, discussed earlier in Section 2.1.4, are approaches towards eliciting these imaginaries.

Building on the increasingly recognised need for the reflective openness and wider stakeholder and public participation in decision making on science and technology innovations discussed in

Section 2.2, the second and third dimensions of responsible innovation are those of reflexivity and inclusion, respectively (Owen *et al.*, 2013). Reflexivity here refers to reflections on the framings, commitments and activities that impact upon innovation; not only at the actor level but also at the institutional level (Wynne, 1993). The notion of inclusion, however, does not go uncontested, with those advocating the approach considered to assume that because science is political, it should be democratic, which in turn should be participatory (Moore, 2010). Others have gone further in their critique, suggesting that participation represents a 'new tyranny' whereby it can exclude, disempower and cover-up oppression (Cooke & Kothari, 2001). Nevertheless, significant developments have been made in evaluating participatory processes to ensure their efficacy in both process and outcome (Chilvers, 2008).

The fourth dimension of responsible innovation is that of responsiveness (Owen *et al.*, 2013), an *'encompassing yet substantially neglected dimension of responsibility'* (Pellizzoni, 2004: 557). In echoing Collingridge's (1980) notion of 'corrigibility', responsiveness refers to the capacity of innovation to *'change shape or direction in response to stakeholder and public values and changing circumstances'* (Stilgoe *et al.*, 2013: 5). A range of mechanisms for building responsiveness exist, including conventional ones such as regulation, standards, the precautionary principle, and moratoria. One that has been used recently in the area of geoengineering has been 'stage-gating', a process that places a series of 'gates' (criteria) at significant stages in the innovation process that must be satisfied in order for an innovation to proceed to the next gate, and ultimately, be realised (Cooper, 1990).

A stage-gate mechanism was used to govern the test-bed component of the Stratospheric Particle Injection for Climate Engineering (SPICE) project (Macnaghten & Owen, 2011). Whilst no actual geoengineering would have taken place, the test-bed was designed to trial a potential delivery mechanism for stratospheric aerosol injection; a hose-pipe attached to a tethered balloon that would deliver water to a height of 1km into the atmosphere. Five stage-gate criteria were outlined: (1) that risks must be identified, managed and deemed acceptable; (2) that the test-bed must be compliant with relevant regulations; (3) that clear communication of the nature and purpose of the project must be made; (4) that applications and impacts must be described and mechanisms put in place that would review them; and (5) that mechanisms be identified to understand public and stakeholder views (see Stilgoe *et al.*, 2013).

Whilst the first two criteria in the stage-gate process were successfully passed, involving elements of reflexivity, the latter three criteria proved more challenging. The test-bed was postponed in September 2011 in order to allow the project personnel to tackle these criteria, whilst in the media a debate had ensued following an announcement of the test-bed's imminence and an open letter from 50 non-governmental organisations citing concerns over the potential for geoengineering to distract from mitigation (a 'moral hazard'). The absence of effective geoengineering governance and a conflict of interest in a patent application for the test-bed technology later led the project team to cancel the test-bed part of the SPICE project. Ultimately, however, the stage-gate framework was deemed to have successfully *'open[ed] up a complex governance discussion, surfacing tensions, framings, tacit assumptions, areas of contestation and, importantly, commitments'* (Stilgoe *et al.*, 2013: 1576), despite its 'modest' ambitions.

Conclusions

The chapter has laid out the contemporary theoretical perspectives on social appraisal. It has determined that the post-normal scientific context in which geoengineering resides demands a particular methodological response in appraisal design, one that accounts for axiological factors from broader stakeholders and publics through the inclusion of an 'extended peer community' (Funtowicz & Ravetz, 1992; 1993). This is reinforced by additional substantive, normative and instrumental imperatives for stakeholder and public engagement in geoengineering appraisal (Fiorino, 1990). Further insights into the nature and different guises of uncertainty and incertitude that bear upon highly complex issues such as geoengineering strengthen this demand for participation, whilst also compelling further particularities in appraisal design (Wynne, 1992a; Stirling *et al.*, 2007). The characterisation of uncertainty inherent to geoengineering the climate means that appraisal must account for its indeterminate uncertainties and issues of ignorance, rather than considering it as an issue of 'risk'. Moreover, appraisal must account for the different types of incertitude that bear upon geoengineering appraisal; uncertainty, ambiguity and ignorance.

In recognising that stakeholder and public participation in geoengineering appraisal is necessary, it should also take an appropriate form, that of genuine dialogue rather than building off models of knowledge deficit. That participation should also take place 'upstream', in advance of significant research and development on geoengineering, and in advance of public controversy (Wilsdon & Willis, 2004). Participatory-deliberative methods are needed in addition to expert-analytic methods, but both approaches have the capacity to 'close down' or 'open up' option choice through power in framings (Stirling, 2008). Methods that are diverse in framing their inputs and reflexive in their presentation should be pursued in the appraisal of geoengineering, as opposed to more narrowly-framed and non-reflexive methods. This will help guard against premature path dependency (David, 2001) and lock-in (Arthur, 1989) to particular options that could lead to controversy. Finally, appraisals of geoengineering should form part of wider ambitions for a framework of responsible innovation, espousing anticipation of possible impacts, reflection on framings, inclusion of stakeholders and publics, and responsiveness to changing circumstances (Owen *et al.*, 2013; Stilgoe *et al.*, 2013).

In the next chapter current appraisals of geoengineering are reviewed and critically analysed so as to both determine their findings, and to critically analyse their designs in order to inform an appropriate methodological response for this thesis.

Chapter 3

A Review of Climate Geoengineering Appraisals

In view of the theoretical perspectives on social appraisal reviewed in Chapter 2, this chapter presents the findings of the first critical analysis of climate geoengineering appraisals. It begins by outlining the method for the systematic review of peer-reviewed and grey literature that underpins the analysis, in Section 3.1. In Section 3.2 a review of the main findings of these appraisals is outlined, with particular attention to those that have employed 'participatory-deliberative' methods. Section 3.3 then presents a critical analysis of the role of framings in shaping appraisal inputs and outputs, and ultimately, epistemic commitments to particular responses to climate change. The chapter concludes by summarising the limitations of existing geoengineering appraisals, with a view towards an effective methodological response.

3.1 Review Method and Results

A systematic strategy for searching and screening peer-reviewed and grey literature was used in order to identify formal and explicit appraisals of geoengineering. The Web of Knowledge electronic database was searched using the parametric terms: 'GEO*ENGINEERING' or 'CLIMATE ENGINEERING'. A total of 272 articles were returned and then screened for their relevance to the aforementioned search aims. 49 relevant articles were then further screened for their scope, where articles appraising ≥ 2 specified geoengineering proposals were included within the review. 9 articles met the inclusion criteria along with a further 12 articles identified using the same search and screening criteria in a general internet search using the Google search engine, giving a total of 21 articles. Of these articles an overwhelming majority of 18 were identified as fully expert-analytic in nature. In order to more widely reflect on emergent participatory appraisals of geoengineering the initial screen strategy was relaxed to include those participatory processes where individual proposals or geoengineering as a collective was appraised. A further four articles were added accordingly, bringing the total to 25 appraisals under review. First published in late 2012, this review has been updated in July 2013 to consider 2 more recent participatory appraisals that have since been published, bringing the total to 27 under review (see Table 3.1).

Table 3.1. Appraisals of geoengineering included for review (adapted from Bellamy *et al.*, 2012).

No.	Source	Appraisal design and methods	Notes on framing
1	Keith & Dowlatabadi (1992)	Expert literature review with select non-technical issues and subjective risk, relating to 8 carbon and solar geoengineering proposals	Climate change impacts frame; subjective opinion of risks; concludes stratospheric aerosols have the lowest COM
2	NAS (1992)	Expert literature review with marginal CO2-equivalent mitigation costs, relating to 7 carbon and solar geoengineering proposals	Climate change impacts frame; costs are based on considerable uncertainties; concludes all geoengineering proposals are low cost and feasible except space reflectors, whilst mechanical cloud albedo and stratospheric aerosols are the most promising
3	Keith (2000)	Expert literature review with select uncertainties, non-technical issues and subjective risk, relating to 7 carbon and solar geoengineering proposals	Climate change impacts frame; subjective opinion of risks; concludes stratospheric aerosols have the lowest COM
4	Levi (2008)	Expert advice with plotting of costs and risks, relating to 6 carbon and solar geoengineering proposals plus mitigation	3 frames: climate change impacts, rapid climate change, insufficient mitigation; subjective plotting of costs and risks; concludes space reflectors are the highest cost and risk, and mitigation is the least risky
5	Bickel & Lane (2009)	CBA relating to 4 carbon and solar geoengineering proposals	3 frames: 'dangerous' climate change, rapid climate change, insufficient mitigation; uses different emission controls scenarios and market and ethical discount rates; concludes mechanical cloud albedo and stratospheric aerosols have greatest direct cost-benefit ratios, recommending their funding for research
6	Boyd (2008)	Expert MCA using 9 criteria (spanning efficacy, affordability, safety and rapidity), relating to 5 carbon and solar geoengineering proposals	2 frames: rapid climate change, insufficient mitigation; technical criteria only with subjective scoring and little attention to uncertainty or sensitivities
7	Robock (2008)	Expert advice relating to 2 solar geoengineering proposals	2 frames: 'dangerous' climate change, insufficient mitigation; concludes geoengineering may be a bad idea
8	Crabbe (2009)	Expert review of modelling simulations applied to coral reefs, relating to 18 carbon and solar geoengineering proposals	2 frames: climate change impacts, insufficient mitigation; recommends further research into carbon geoengineering proposals, particularly air capture and storage, biochar and afforestation
9	Feichter & Leisner	Expert literature review relating to 3 solar geoengineering proposals	2 frames: climate change impacts, insufficient mitigation; concludes none of

	(2009)		the schemes are a sole solution to climate change
10	Irvine & Ridgwell (2009)	Expert literature review with select pros and cons and subjective risk, relating to 5 solar geoengineering proposals	2 frames: dangerous' climate change, insufficient mitigation; subjective opinion of risks; concludes geoengineering should not be relied upon to stop climate change but recommends research in case of climate 'emergency'
11	Izrael *et al.* (2009)	Expert literature review with subjective assessment (spanning feasibility and efficacy), relating to 13 carbon and solar geoengineering proposals	2 frames: climate change impacts, insufficient mitigation; subjective opinion of feasibility; concludes stratospheric aerosols can be the most effective
12	Lenton & Vaughan (2009)	Radiative forcing potential calculations relating to 19 carbon and solar geoengineering proposals	2 frames: 'dangerous' climate change, insufficient mitigation; assumes strong mitigation scenario baseline; concludes only stratospheric aerosols, mechanical cloud albedo and space reflectors can create a pre-industrial state of climate
13	Royal Society (2009)	Expert literature review with MCA using 4 criteria (efficacy, affordability, safety and timeliness), plotted and relating to 20 carbon and solar geoengineering proposals and CCS; plus telephone interview survey and focus groups exploring public perceptions, relating to 3 carbon and solar geoengineering proposals	3 report frames: 'dangerous' climate change, insufficient mitigation, 2°C policy target; geoengineering definitions frame for public engagement; MCA features technical criteria only with subjective scoring; MCA concludes that stratospheric aerosols, air capture and storage and enhanced weathering are the most effective, afforestation is the most affordable, stratospheric aerosols, desert albedo and CCS are the most rapid, and air capture and storage, urban albedo and CCS are the safest; public engagement concludes that perceptions were generally negative
14	Moore *et al.* (2010)	Linear response model simulations compare limiting sea-level rise, relating to 5 carbon and solar geoengineering proposals	2 frames: climate change impacts, climate 'emergency'; assumes geoengineering does not affect exchange processes between the atmosphere, biosphere and oceans; concludes that bioenergy with carbon sequestration is the least risky and most desirable for limiting sea-level rise
15	NERC (2010)	Deliberative public dialogue exploring perceptions (spanning public groups, discussion groups, online survey and open access events), relating to 9 carbon and solar geoengineering proposals	Insufficient mitigation frame for report; 2 public dialogue frames: pros and cons, climate 'emergency'; climate emergency framing may have influenced stated acceptability of geoengineering; concludes that carbon geoengineering proposals are preferred to solar proposals, with afforestation and biochar favoured most
16	Spence *et al.* (2010)	Face-to-face interview survey exploring perceptions, relating to geoengineering proposals as a collective†	2 report frames: 'dangerous' climate change, Climate Change Act; geoengineering definitions frame for interview survey; uses simple quantitative measures; concludes that most people do not know what geoengineering is

			but would support it
17	Bellamy & Hulme (2011) †	Online survey and focus groups exploring perceptions, relating to geoengineering proposals as a collective and several mitigation options	Rapid climate change frame; presents geoengineering as one option of a range of possible responses to climate change; concludes geoengineering is unfavourably received
18	Fox & Chapman (2011)	Expert literature review and ranking applied to engineering feasibilities, relating to 10 carbon and solar geoengineering proposals	3 frames: climate change impacts, rapid climate change, insufficient mitigation; arbitrary ranking of feasibilities; concludes afforestation is the most feasible proposal
19	US GAO (2011)	Expert technology assessment (spanning maturity, effectiveness, cost factors and consequences), relating to 14 carbon and solar geoengineering proposals; plus online survey and focus groups exploring public perceptions, relating to 4 carbon and solar geoengineering proposals	3 report frames: climate change impacts, rapid climate change, insufficient mitigation; geoengineering definitions frame for public engagement; includes foresight exercise using scenarios to elicit views of future research; technology assessment concludes that all geoengineering proposals are at TRL 2, except stratospheric aerosols which are the least mature (TRL 1) and air capture and storage which is the most mature (TRL 3); public engagement concludes that most are unfamiliar with geoengineering but are open to research, whilst showing concern about safety and governance
20	Irvine *et al.* (2011)	AOGCM simulations compare global and regional effects, relating to 3 solar geoengineering proposals	3 frames: climate change impacts, insufficient mitigation, 2°C policy target; limitations to regional modelling of effects; concludes none of the schemes reverse climate changes under a doubling of CO_2
21	Jones *et al.* (2011)	AOGCM simulations compare climatic impacts, relating to 2 solar geoengineering proposals	2 frames: climate change impacts; alternative to mitigation; limitations to cloud modelling; concludes geoengineering is unlikely to avoid significant regional climate changes
22	Mercer *et al.* (2011) †	Online survey exploring perceptions, relating to solar geoengineering proposals as a collective	3 article frames: societal responses to climate change, inexpensive, risks; 2 survey frames: pros and cons, climate 'emergency'; risk of constructed preferences; concludes the public supports research into solar geoengineering
23	Parkhill & Pidgeon (2011)†	Deliberative workshops exploring perceptions, relating to 1 solar geoengineering proposals: stratospheric aerosols	Societal responses to climate change frame; presents geoengineering as a risk issue; concludes that participants show a reluctant acceptance of a delivery mechanism test-bed for stratospheric aerosols
24	Vaughan & Lenton (2011)	Expert literature review with select efficacies and feasibilities, relating to 19 carbon and solar geoengineering proposals	2 frames: rapid climate change, insufficient mitigation; assumes strong mitigation scenario baseline; concludes that geoengineering is not an alternative to mitigation, but could complement it
25	Russell *et al.*	Expert literature review with select eco-	Climate change impacts frame; con-

	(2012)	logical impacts, relating to 5 carbon and solar geoengineering proposals	cludes that research on ecological impacts of geoengineering is needed before large-scale field trials or deployment
26	Macnaghten & Szersynski (2013)‡	Deliberative focus groups exploring public perceptions, relating to 1 solar geoengineering proposal	5 frames: experience of weather and climate, policy responses to climate change, insufficient mitigation, environmental and civil society perspectives on geoengineering, geopolitical history of weather and climate modification; concludes there are key conditions for public acceptance of solar radiation management
27	Corner *et al.* (2013) ‡	Deliberative workshops exploring public perceptions, relating to 4 carbon and solar geoengineering proposals	Societal responses to climate change frame; concludes naturalness is a key determinant of public perceptions of geoengineering

Acronyms: atmosphere-ocean general circulation model (AOGCM); cost-benefit analysis (CBA); cost of mitigation (COM); multi-criteria analysis (MCA); technology readiness level (TRL). † indicates appraisals included after the initial search and screen, ‡ indicates appraisals included after this review was first published. The information presented in this table is necessarily selective.

3.2 Findings of Geoengineering Appraisals

In this section the main findings of climate geoengineering appraisals are outlined, with reference to those employing 'expert-analytic' methods in Section 3.2.1, and with particular attention to those that have employed 'participatory-deliberative' methods in Section 3.2.2.

3.2.1 Expert-analytic appraisals of geoengineering

Those appraisals of geoengineering that employed expert-analytic methods (appraisals 1 – 14, 18 – 21, and 24 – 25 in Table 3.1) predictably dealt with four main technical issues: efficacy, feasibility, economics, and risk. A limited number of the review-based expert-analytic appraisals also considered some of the broad governance and ethical issues associated with geoengineering (e.g. Royal Society, 2009), which are considered in the next section.

Of those appraisals that assessed matters of efficacy in geoengineering proposals did so with respect to three broad issues. The first relates to the significance of any reduction in global temperature, be it through either an increase in planetary surface albedo or a decrease in atmospheric

CO_2 concentration. The second and third, and much less considered, issues relate to the significance of the speed with which a proposal might realise that reduction in temperature, and the significance of any reduction to specific climate change impacts, respectively. Under speed of effect, stratospheric aerosol injection and desert albedo enhancement have performed most highly (Royal Society, 2009). Under specific climate change impacts, bioenergy with carbon sequestration (BECS) has been shown to be the most desirable for limiting sea level rise (Moore *et al.*, 2010).

With respect to those appraisals concerned with assessing the significance of any reduction in global temperature, stratospheric aerosol injection is most often found to perform most highly, in the main for its radiative forcing potential (Izrael *et al.*, 2009; Royal Society, 2009; Lenton & Vaughan, 2009; Jones *et al.*, 2011; Vaughan & Lenton, 2011). Cloud albedo enhancement (Lenton & Vaughan, 2009; Jones *et al.*, 2011; Vaughan & Lenton, 2011) and space reflectors (Lenton & Vaughan, 2009; Royal Society, 2009; Vaughan & Lenton, 2011) have also performed the most highly along the same lines, whilst desert albedo enhancement has done so when compared with other surface albedo modification (SAM) proposals (Irvine *et al.*, 2011). By contrast, air capture and storage has performed most often the most highly for its CO_2 removal potential (Crabbe, 2009; Lenton & Vaughan, 2009; Royal Society, 2009). Enhanced weathering (Royal Society, 2009) and iron fertilisation (Boyd, 2008) have also performed the most highly with this criterion.

Of those appraisals that assessed matters of feasibility in geoengineering proposals did so with respect to two broad issues. The first relates to technical feasibility, where afforestation is most often considered the most feasible (NAS, 1992; Fox & Chapman, 1992), but where stratospheric aerosol injection is a close second (*ibid*). The second feasibility issue relates to technical maturity, where air capture and storage has been assessed as possessing the highest technology readiness level (TRL) of the proposals under review (US GAO, 2011). Stratospheric aerosol injection has been assessed to show the lowest TRL of those geoengineering proposals that were considered, but has elsewhere been argued as the most mature, for its 'realistic' realisation before 2015 and its natural volcanic analogues (Izrael *et al.*, 2009).

Appraisals of geoengineering that assessed matters of economics did so with respect to three broad issues. The first relates to cost or affordability in their simplest terms, where afforestation (Royal Society, 2009), cloud albedo enhancement (Boyd, 2008), crop albedo enhancement (Irvine & Ridgwell, 2009), and iron fertilisation (Levi, 2008) have all been assessed as the most affordable proposals. The second issue in economic appraisals relates to the equivalent cost of mitigation ($ / t CO_2), where stratospheric aerosol injection has frequently been assessed as having the lowest cost (NAS, 1992; Keith & Dowlatabadi, 1992) or second only to, curiously, space reflectors (Keith, 2000). The third issue relates to cost-benefit analysis, where cloud albedo enhancement has been assessed as having the most favourable cost-benefit ratio (1: 5000), followed by stratospheric aerosol injection (1: 25) (Bickel & Lane, 2009).

Those appraisals that assessed matters of risk largely did so with respect to a general 'risk' assessment, including generic issues of side effects and safety. Under such assessments, air capture and storage most often emerged as the proposal posing the least risk (Keith, 2000; Boyd, 2008; Royal Society, 2009). Concurrently, urban albedo enhancement (Irvine & Ridgwell, 2009; Royal Society, 2009), crop albedo enhancement (Irvine & Ridgwell, 2009), and BECS (Levi, 2008) have also been assessed as the least risky, and in limited cases alongside broad mitigation and carbon capture and storage (Levi, 2008; Royal Society, 2009). By contrast, stratospheric aerosol injection has been identified most often as posing the highest risk (Keith & Dowlatabadi, 1992; Keith, 2000; Levi, 2008; Irvine & Ridgwell, 2009), with iron fertilisation (Boyd, 2008; Royal Society, 2009), space reflectors (Irvine & Ridgwell, 2009), and desert albedo enhancement (Royal Society, 2009) also being assessed as such. Other, much less considered, issues included controllability (switch off < 1 year), where all proposals were viewed as controllable with the exception of surface albedo enhancement proposals; and risks pertaining to specific impacts, such as regional weather patterns, where cloud albedo enhancement and stratospheric aerosol injection have both been shown to depend upon the location of application (Jones *et al.*, 2011).

Under the expert-analytic and technically-focussed appraisals of geoengineering, some clear patterns emerge with respect to the relative performance of different proposals. Solar geoengineering proposals, and in particular stratospheric aerosol injection, but also cloud albedo enhancement, space reflectors and desert albedo enhancement, dominate the upper echelons of proposal rankings for efficacy criteria. Stratospheric aerosol injection also comes to the fore in proposal rankings for feasibility criteria, alongside afforestation and air capture and storage. Stratospheric aerosol injection once again leads option rankings for economics criteria, alongside other solar geoengineering proposals, in particular cloud albedo enhancement. The relative performance of options under risk-based criteria are, however, quite different. Here, the rankings are reversed, with stratospheric aerosol injection and the other solar geoengineering proposals performing poorly, and less 'effective' or 'economical' proposals such as urban albedo enhancement or air capture and storage performing more highly.

3.2.2 Geoengineering governance and ethics

Two of these expert-analytic appraisals also considered issues for the governance of geoengineering: the Royal Society (2009) and the US GAO (2010). The proposals have been considered by some as being capable of *'cut[ing] through the diplomatic bottlenecks which slow down and dilute the effectiveness of international treaties such as the Kyoto Protocol'* (Hulme, 2009: 315). However, the governance challenges of geoengineering the climate are not so simple, and are dependent upon the particular technologies under consideration and the manners in which they might be deployed. For example, stratospheric aerosol injection may require a commitment for hundreds of years, bringing about institutional and physical lock-in (Bengtsson, 2006). The Royal Society (2009) outlines two key characteristics that might assist in identifying suitable governance mechanisms: encapsulation and reversibility. Those proposals that are encapsulated and do not release materials into the environment, and those that are reversible, for example, will have different governance requirements to those that do release materials and are irreversible. As such, it might be considered prudent to invoke the precautionary principle, echoing calls by Bodansky (1996).

The Oxford Principles (Rayner *et al.*, 2013) have been proposed as five, high-level principles of equal status for geoengineering governance. They argue that: (1) geoengineering should be regulated as a public good; (2) decision making on geoengineering should involve public participation; (3) geoengineering research and its results should be disclosed and openly published; (4) possible impacts should undergo independent assessment; and (5) governance structures for geoengineering should be in place before deployment. These key principles have since been adopted by the UK House of Commons Science and Technology Committee (2010), and further developed during the Asilomar Conference on Principles for Research into Climate Engineering Techniques (ASOC, 2010). As high-level principles, however, they do not delineate the form that public engagement should take beyond mere 'notification' or 'consultation'. Moreover, whilst recognising the risk of the 'technology control dilemma' (Collingridge, 1980), it does not delineate how flexibility should be incorporated to governance. Without it, governance architecture cannot know the impacts of geoengineering until significant development has taken place; by which time governance could not exercise adaptiveness over the trajectories of its innovation.

The Royal Society (2009), and the US GAO (2010) both note that a number of geoengineering proposals could, in point of fact, be adequately governed through existing national laws and international agreements. For example, iron fertilisation was proposed as being governable through the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (IMO, 2007) and has since been ratified (IMO, 2013). This has followed growing concerns first aired in the 9th Conference of the Parties of the United Nations Convention on Biological Diversity where Decision IX/16 on biodiversity and climate change in 2008 was made. This decision called for a moratorium on all geoengineering which might affect biodiversity in line with Article 14 of the convention.

Subjective interpretations of other international agreements could bring barriers to geoengineering. For example, the Long-Range Transboundary Air Pollution Convention and the 1990 amendment to the Clean Air Act could hinder the use of stratospheric aerosols in Europe and the United States (Merrill, 1997). On the other hand, these treaties did not account for geoengineering during their conception and could be renegotiated. Some argue that the 1977 UN Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques (ENMOD) would make any geoengineering illegal (MacCracken, 2006), but overlook the treaty's specific preservation of the right to use such techniques for peaceful purposes (Article 3.1) (Virgoe, 2009).

Existing mechanisms are reflected in other research by Humphreys (2011), who has divided the geoengineering proposals amongst two categories with different governance implications: territorial and commons. Those operating within the territorial sovereignty of states could evidently be governed within national boundaries, but those operating in the international commons, such as the sea (e.g. iron fertilisation), the atmosphere (e.g. stratospheric aerosol injection) or space (e.g. space reflectors), would require international agreement. For those proposals that would operate in the global commons, Virgoe (2009) proposes three possible routes for governance: multilateral, consortium-led or unilateral. Multilateral governance through an international body such as the UN is often voiced as the most preferred route. Indeed, there have been recent calls for decision making on geoengineering to take placed within the United Nations Framework Convention on Climate Change (UNFCCC), supported by research evaluation under the Intergovernmental Panel on Climate Change (IPCC) (Zürn & Schäfer, 2013).

There of course exists the possibility for action without agreement, or unilateral action, which would seem a very real prospect given the ostensible effectiveness, feasibility and cheapness of particular geoengineering proposals such as stratospheric aerosol injection. In response to this threat, global transparency and cooperation has been recommended (Blackstock & Long, 2010). The Solar Radiation Management Governance Initiative (SRMGI) has since been established, which has put forward a number of governance recommendations calling for further research and regulated testing amongst other items, whilst cautioning against the likely difficulty of enforcing any moratorium on research (SRMGI, 2011). International conversations were also deemed critical for a suite of technology proposals that would affect the global climate, with some early research on African perspectives on solar geoengineering emerging from the project (SRMGI, 2013).

Many of these governance issues arise from concerns about the ethics of geoengineering the climate. As part of its foray into governance, the Royal Society (2009) also undertook a preliminary examination of possible ethical issues. It identified three overarching ethical positions with regards geoengineering: consequentialist, deontological and virtue-based. The outcomes of geoengineering actions are the moral code of the consequentialist ethical position (commonly discussed as 'the end justifies the means'); whereas the rules or character of actions are the moral codes of the deontological and virtue-based ethical positions respectively. The ethics of geoengineering are, however, subject to a proviso as they are complicated by its diverse forms which do not all necessarily conform to the same ethical issues (Gardiner, 2010) or indeed, ethical frames.

Echoing earlier concerns about 'defeatist' adaptation efforts (Pielke Jr., 2007), perhaps the most prevalent ethical concern raised in debates about geoengineering relates to the notion of a 'moral hazard' whereby the promise of a 'techno-fix' might remove responsibility and hinder mitigation efforts (Royal Society, 2009). On the other hand, early empirical investigation with publics indicates that the idea of geoengineering could, in fact, galvanise mitigation efforts rather than harm them (Royal Society, 2009; NERC, 2010). Other ethicists raise ethical issues about consent. Questions of how to effectively represent the views of stakeholders are raised, which in the case of geoengineering means the population of the entire planet. This issue becomes increasingly difficult when considering the representation of stakeholders residing in the worlds' less economically and politically developed nations (Adger *et al.*, 2006). Even if consent were attained, further ethical issues are raised about the nature of possible consequences as a result of geoengineering the climate, relating to their distribution (Morrow *et al.*, 2009) and reversibility (Jamieson, 1996) of effects, control of 'the thermostat' (Robock, 2008) and misuse (Corner & Pidgeon, 2010).

A supposed asymmetry exists between deliberate and inadvertent manipulations of the climate. This asymmetry is a familiar feature of 'common sense' morality debates with something being done deliberately often seen as worse than something being done inadvertently (Jamieson, 1996). This perhaps oversimplified view of diminished responsibility has its origins in the Catholic moral theology 'Doctrine of Double Effect'. However, for example, the consequentialist perspective might argue that although there may be extrinsic moral differences between murder and passive euthanasia, there are no intrinsic ones; meaning that the two acts have the same consequences irrespective of their intentions (Singer, 1993). Moreover, the deontological perspective might argue that thought experiments with the 'ticking time bomb scenario' can justify advertent 'lesser evils' to avoid inadvertent 'greater evils' (Luban, 2007). In this neo-Kantian sense, geoengineering could be construed as the deliberate 'lesser evil' to counteract the inadvertent 'greater evil' of anthropogenic climate change.

In response to the ethical issues posed by geoengineering some ethicists have attempted to outline conditions to guide research, development and implementation. For example, Jamieson (1996) outlines four conditions for geoengineering to be morally permissible: the project must be technically feasible; its consequences should be predicted reliably; it should produce states that are socio-economically preferable to alternatives; and it should not violate any important, well-founded ethical principles or considerations including democratic decision making, irreversible environmental changes and the significance of learning to live with nature. Similarly, Morrow *et al.* (2009) stipulates three ethical principles for geoengineering research and development: respecting consent; maintaining beneficence and justice; and minimising the extent and intensity of experimentation to test hypotheses. On the other hand, many of these conditions are likely unattainable were they to be vehemently upheld, leaving eventual deployment seemingly improbable (Bunzl, 2009).

3.2.3 Participatory and deliberative appraisals of geoengineering

Rather than seeking to evaluate a range of predetermined technical issues, those appraisals of geoengineering that used participatory and deliberative methods (appraisals 13, 15 – 17, 19, 22 – 23, 26 – 27 in Table 3.1) sought to elicit public attitudes towards, and perceptions of, specified aspects of the different proposals. The appraisals dealt with geoengineering either as a collective (appraisals 16, 17 in Table 3.1), as two distinct sets of proposals (carbon geoengineering and solar geoengineering) (appraisals 22, 26 in Table 3.1), or as individual proposals (appraisals 13, 15, 19, 23, 27 in Table 3.1).

Awareness of geoengineering as a collective has been shown to be low amongst publics (NERC, 2010; Spence *et al.*, 2010), with some recent improvement (Mercer *et al.*, 2011). Despite the relatively low levels of awareness, some early research has shown a high level of support for geoengineering proposals as a response to tackling climate change. Indeed, a nationally representative study of attitudes in the UK (n = 1,822) showed that 47% of respondents in face-to-face interviews either supported or strongly supported them, whilst only 4% either opposed or strongly opposed them (Spence *et al.*, 2010). In the UK-based Experiment Earth public dialogue on geoengineering none of the participants expressed opposition to geoengineering on matters of principle (NERC, 2010). On the other hand, other research has shown generally negative attitudes towards geoengineering. Through public focus groups and a (UK) nationally representative telephone survey (n = 1,000), geoengineering has been met with ethical objections (Royal Society, 2009). General opposition has also been found through other public focus groups and an online survey (n = 287), where only 2.8% of respondents expressed a preference for geoengineering as a response to abrupt climate change, when considered against a diversity of mitigation alternatives (Bellamy & Hulme, 2011).

Exploration of public attitudes towards the relationship between geoengineering and mitigation has shown that research and development into low carbon technologies is viewed as a priority over and above that for geoengineering (Royal Society, 2009). At the same time, it is understood amongst publics that mitigation efforts may be insufficient to tackle climate change without additional support from geoengineering (NERC, 2010). Indeed, participants in the Experiment Earth public dialogue expressed a desire to combine a number of different geoengineering proposals with mitigation at different scales, contrasting with concerns that geoengineering might induce a 'moral hazard' whereby mitigation efforts might be hampered (*ibid*). This perception counter to moral hazard argumentation has been replicated elsewhere (Royal Society, 2009), where participants have expressed a likely motivation to undertake personal mitigation action where governments or industry are seen to be investing in geoengineering research or deployment.

In recent deliberative public workshops the notion of 'naturalness' has been highlighted as a key lens through which publics engage with geoengineering (Corner *et al.*, 2013), much as it has with other emerging technologies such as genetically modified (GM) crops and animal cloning (e.g. Gaskell *et al.*, 1999). The 'messing with nature' issue has been shown to resonate with a number of broad and contesting themes that bear upon perceptions of geoengineering. The first is that geoengineering could be used as a tool to preserve, but also threaten nature. Rather than making a 'sustainable nature', it has also been viewed as making the future less secure, and posing unintended consequences from whence nature might 'bite back'. Geoengineering has been viewed as representative of society 'out of sync' with nature, but that on the other hand could be 'compatible' with natural processes.

The extent to which geoengineering proposals support natural processes featured as an important 'criterion' towards assessing geoengineering in future research as well as an attitude towards geoengineering itself in the Experiment Earth public dialogue (NERC, 2010). In addition to determining the different benefits and costs that geoengineering might bring, participants in the study were supportive of future research that would further explore practical and ethical criteria, including the risk of a moral hazard, the controllability of geoengineering and its different proposals, including detailed assessments of impacts, the reversibility of any impacts that might take place, how the proposals might be governed, and the conditions of urgency under which they might be deployed: the definition of a 'climate emergency'.

In seeking to understand the factors that underpin perceptions of geoengineering as a collective, the Royal Society (2009) laid down three aspects seen as likely predictors. These aspects relate to the transparency of the actions, motivations and purposes of actors; the vested interests driving research and development; and concern for environmental impacts and responsibility for their resolution. The seriousness of climate change itself has been identified as a significant influence on more favourable attitudes towards geoengineering (NERC, 2010), whilst counter moral hazard reasoning has been found to be more pronounced amongst those sceptical of climate change. Others have examined the underlying values and beliefs that influence perceptions of geoengineering. In considering the Cultural Theory of Risk (Douglas, 1970; Douglas & Wildavsky, 1982; Thompson *et al.*, 1990), those more supportive of geoengineering have shown a hierarchical bias, whilst those cautioning against its dangers have shown an egalitarian bias (Bellamy & Hulme, 2011).

Participatory and deliberative appraisals of geoengineering have consistently shown a difference in public attitudes between its two subset classes: carbon geoengineering and solar geoengineering. Indeed, support or strong support for carbon geoengineering proposals has been shown to be higher (47%) than for solar geoengineering proposals (40%) (Spence *et al.*, 2010). Similarly, carbon geoengineering proposals have been viewed as the preferred method of geoengineering in the Experiment Earth public dialogue, whilst solar geoengineering proposals have received less support for their inability to tackle the 'root cause' of climate change: greenhouse gases (NERC, 2010). The Royal Society (2009) has gone further in suggesting that a significant difference in public perceptions may transcend the carbon and solar class dichotomy, with black-box engineered proposals being viewed differently to those enhancing Earth systems.

In an online survey (n = 3105) spanning the USA, UK and Canada, Mercer *et al.* (2011) have explored cross-cultural public attitudes towards solar geoengineering proposals in particular. Whilst the study found that 72% of respondents supported or somewhat supported research into solar geoengineering proposals, this support became less clear under a prospective immediate deployment and climate emergency. Paradoxically, in echoing other research that has explored the issue of naturalness, 64% of respondents felt that humans should not be manipulating nature through solar geoengineering, and 43% were unsure as to whether it would help or hurt the planet. The researchers demarcate two distinct group perspectives on solar geoengineering: those of 'supporters' and those of 'detractors' which made up 29% and 20% of the respondents respectively. Interestingly, supporters and detractors both constituted approximately a third of each nation's respondents, except where detractors in the USA which were slightly higher than in the UK or Canada. Concurrently more moderately political respondents constituted supporters, whilst more politically conservative respondents constituted detractors. 2.6% of all respondents were believers in 'chemtrail' conspiracy theories, whilst 14% believed the conspiracy was 'partly true'.

In contrast with Mercer *et al.* (2011), deliberative focus groups convened to explore solar geoengineering conducted by Macnaghten & Szersynski (2013) have not found distinct groups of supporters and detractors. Instead, more nuanced positions emerged that amount to a series of five conditions for the public acceptance of solar geoengineering. These conditions scrutinise solar geoengineering for its plausibility with respect to (1) confidence in climate science as a reliable guide to policy; (2) confidence in the ability of research to predict side effects; (3) confidence in the ability of research to demonstrate efficacy; (4) confidence in effective governance of solar geoengineering; and (5) confidence in the capacity of democracy to accommodate solar geoengineering. In concluding, the research questions the attainability of these conditions given the 'anti-democratic' constitution of possible unilateral solar geoengineering. Of course, it is likely that Macnaghten & Szersynski (2013) intended to refer to particular proposals within the solar geoengineering class (e.g. stratospheric aerosol injection), as not all proposals from the class are not conducive to such a constitution (e.g. urban albedo enhancement).

A limited number of participatory and deliberative appraisals of geoengineering have begun to explore attitudes towards and perceptions of specific proposals. The Experiment Earth public dialogue (NERC, 2010) is the most advanced of these appraisals, in exploring several carbon geoengineering and solar geoengineering proposals. Prior to that, the Royal Society (2009) included a preliminary elicitation of public attitudes towards stratospheric aerosol injection and iron fertilisation. Since then, Parkhill & Pidgeon (2011) have conducted an elicitation of attitudes towards stratospheric aerosol injection as part of the Stratospheric Particle Injection for Climate Engineering (SPICE) project test-bed public consultation (see also Pidgeon *et al.*, 2013).

Afforestation has been seen as the most preferred of carbon geoengineering proposals and of geoengineering more broadly, closely followed by biochar (a process for pyrolyzing and burying organic carbon), and foremost because of their perceived naturalness, their local situation, and their complementarity with mitigation (NERC, 2010). However, their large scale and likely impacts on biodiversity were cited as concerns, whilst afforestation was also critiqued for its slow rate of CO_2 sequestration. Air capture and storage was also viewed positively for its complementarity to mitigation and its controllability. Its naturalness has been interpreted differently by different participants, where whilst it was 'natural' in that it returned CO_2 to its place of origin, its role as an artificial tree and 'end-of-pipe' solution invited debate over whether natural afforestation should take its place or whether CO_2 should be captured before its release. Concurrently, it has been seen as potentially aesthetically displeasing with parallels made to existing onshore wind turbines, and as presenting concerns over the safety of stored CO_2.

In contrast with those other carbon geoengineering proposals, ocean-based enhanced weathering has been perceived as 'engineered' rather than natural and was viewed very poorly for its likely impacts on marine life (NERC, 2010). Ocean iron fertilisation has been seen as more natural than ocean-based enhanced weathering, potentially bringing benefits to marine life through enhanced nutrient provision. However, the uncertainties of the proposal, the need for international regulation, and its irreversible impacts were significant concerns that left ocean iron fertilisation with little support in the Experiment Earth public dialogue. Moreover, it was seen as a case in point of a 'slippery slope' whereby tampering with nature in one regard might lead to others. Elsewhere the proposal has received mixed support, with 39% of participants in a telephone survey lending their support and 34% voicing opposition (Royal Society, 2009).

Cloud whitening has been seen as the most preferred of solar geoengineering proposals, but has still shown little public support (NERC, 2010). The proposal has been understood as natural, but also potentially expensive and damaging to the tourism industry through its lessening of sunlight. Urban albedo enhancement has been seen as a simple, yet ingenious idea, but has ultimately received little support for its likely expenses and impracticalities. Space reflectors have, perhaps unsurprisingly, been viewed as science fiction and received much public interest. However, upon examining the proposal in more detail it became clear that it was seen as 'unnatural', 'scary' and 'dangerous', whilst failing to address the cause of climate change and requiring a lengthy development time and international regulation.

Stratospheric aerosol injection has been unpopular with UK publics (NERC, 2010), receiving as little support as 22% and as much opposition as 47% (Royal Society, 2009). It has been seen as a quick fix for a potential climate 'emergency', but that it would not address the cause of climate change and might induce a moral hazard. These findings have been reinforced by the research into public engagement with the SPICE project test-bed, where it was viewed as an unnatural 'stop gap' posing significant geopolitical risks and challenges for governance and control, including consent and codes of conduct (Parkhill & Pidgeon, 2011; Pidgeon *et al.*, 2013). These challenges left some participants questioning whether research into such a contested technology should even take place, echoing concerns voiced by Hulme (forthcoming) whilst others argued that value could be derived from researching all avenues of possibility. Overall, participants in the engagement expressed a 'reluctant', or 'conditional' acceptance of research into stratospheric aerosol injection, which has been reaffirmed more recently (Macnaghten & Szersynski, 2013), echoing earlier public perceptions of nuclear energy (Bickerstaff *et al.*, 2008).

3.2.4 Media discourse analyses of geoengineering

At the same time as researchers have begun to conduct participatory and deliberative appraisals of geoengineering, others have started to explore public understandings of geoengineering. Media discourse analyses have recorded the appearance of media frames that may impact upon public perceptions. Upon the emergence of geoengineering in the UK print media, six frames have been identified: risk, governance and accountability, economics, morality, security and justice (Porter & Hulme, 2013). These concerned frames represent those that could be equally applicable to other controversial issues, and reveal frame construction assumptions about humanity's relationship with nature. A metaphor-oriented discourse analysis of UK print media reveals three different master-metaphor planetary frames that emerge from an overarching argument from catastrophe: 'the planet is a body', 'the planet is a machine', and 'the planet is a patient or addict' (Nerlich & Jaspal, 2013).

Other, international analyses of geoengineering metaphors in two newspapers in the UK and in the USA have revealed three more frames: war, controllability and health; which have been used in different ways to support or oppose geoengineering research (Luokkanen *et al.*, 2013). By contrast, in the US print and online media frames have centred less around concerns, but largely around the 'spectacle' of geoengineering and its possible role as a 'solution' to climate change (Buck, 2012). Indeed, this research also found that 70% of assertions on geoengineering made in the media were by scientists, of which nine scientists were responsible for 36% and just two, David Keith and Ken Caldeira, comprising 15%. Others still have studied frames in the broad scientific literature, revealing risk-benefit, governance and natural balance as significant (Huttunen & Hildén, 2013).

3.3 Framing Geoengineering Appraisal

In this section a reflexive critical analysis of geoengineering appraisals is undertaken with respect to the role of framings in shaping appraisal inputs and outputs, and ultimately, epistemic commitments to particular responses to climate change. First, the definition of the problem or issue in question and the contextual situation of geoengineering proposals are examined in Section 3.3.1. Second, the methods and criteria selected to conduct these appraisals are examined in Section 3.3.2. Third, the reflexivity with which appraisal outputs are conveyed and the overall recommendations of geoengineering appraisals are examined in Section 3.3.3.

3.3.1 Problem definition and contextual situation

The foremost framings in geoengineering appraisals relate to the ways in which the 'problem' or issue is defined, and the context in which options reside. The initial review identified six frames, each of which situated geoengineering within scientifically defined terms around climate change and the need to alleviate its potential risks (see Table 3.2). Such frames echo with those discourses of risk that have been shown to permeate other emergent sciences and technologies such as biotechnology and nanotechnology (Wynne, 2005). The nature of the risk discourse adopted several different frames, ranging from unspecified or specified climate change impacts to special climate 'emergency' conditions. These conditions included the onset of rapid or 'dangerous' climate change or large scale climate 'tipping points'.

Ostensibly insufficient mitigation efforts also featured prominently in appraisal discourses, whilst policies such as the UK Climate Change Act 2050 target and the EU 2°C boundary object also appeared. Few appraisals adopted a broader 'societal responses' to climate change frame and fewer still adopted a frame depicting geoengineering as an alternative to mitigation. After the inclusion of the two most recent participatory appraisals in the review, three further frames emerged that adopted broader problem definitions around experiencing weather and climate, stakeholder perspectives on geoengineering, and the geopolitical history of weather and climate modification.

Table 3.2. Frequency of different problem definitions in geoengineering appraisals (adapted from Bellamy *et al.*, 2012).

Frame	Frequency
Insufficient mitigation	15 (16)
Climate emergency	15
Climate change impacts	13
Climate policy	3 (4)
Societal responses	2 (3)
Mitigation alternative	1
Geopolitical history†	(1)
Stakeholder perspectives†	(1)
Weather and climate†	(1)

Frames were elicited from article introductions and methods. Most appraisals used multiple frames, which are counted here separately. † indicates unique frames elicited from appraisals included after this review was first published, with numbers in brackets indicating updated frequencies.

The problem definitions adopted by most geoengineering appraisals relate to just two assertions; that efforts to mitigate climate change are insufficient and that there is a significant risk of there being a climate 'emergency'. These and other narrow framings represent particular sets of values and assumptions that exclude other, equally legitimate, visions of the future circumstances under which geoengineering might be considered. Obvious omitted visions (or social 'imaginaries') include alternative purposes of geoengineering that might be linked with profit, social control or military applications. The anticipation of social and ethical implications is also excluded, as is recognition of the complex and unknown social, cultural-institutional, and geopolitical futures embedded within such visions.

Frames of problem definition are particularly potent in participatory processes, where different visions can exert significant power upon participants' appraisals. For example, during the NERC Experiment Earth public dialogue facilitators and experts inadvertently adopted a climate emergency frame which is likely to have influenced the perceived acceptability of geoengineering proposals through the implication of necessity (NERC, 2010; Corner *et al.*, 2011). In the same way particular proposals were also described as being more or less 'natural' which later proved to be an important determinant of public perception. Climate emergency framings have also been deployed in online survey research that has elicited apparent public support for solar geoengineering research (see Mercer *et al.*, 2011; *cf.* Bellamy & Hulme, 2011).

The prevalence of climate emergency and insufficient mitigation frames in geoengineering appraisals effectively serves to necessitate geoengineering research and relegate the seemingly inadequate mitigation and adaptation alternatives to exclusion. As a consequence if alternative courses of action are included at all they are commonly and narrowly represented by other geoengineering proposals, ignoring the wider portfolio of options for tackling climate change. What is more, those proposals that have been included are present because of normative reasons of promise or prominence based on incumbent knowledge, offering a classic example of cognitive lock-in (Johnson *et al.*, 2003). For example, they have been selected on the basis of their being 'promising suggestions' (Feichter & Leisner, 2009); their 'promise for affecting global climate' (Bickel & Lane, 2009); their prominence in 'popular and scientific media' (Boyd, 2008); and their 'plausibility' (Parkhill & Pidgeon, 2011); or even on no apparent basis at all (US GAO, 2011).

A mean of 8.5 different geoengineering proposals were appraised per article in the initial review, composed of an even 4 carbon and solar proposals per article. However, an analysis of the frequency of different geoengineering proposals featured in appraisals reveals an emergent closing down upon particular ideas (see Figure 3.1). A clearly tiered distribution shows that certain proposals are receiving significantly more attention than others. Three of arguably the most controversial geoengineering proposals occupy positions in the top four most frequently appraised proposals: stratospheric aerosols, space reflectors, and iron fertilization. Stratospheric aerosols are by far the most frequently appraised proposal, appearing in 24 of the 27 appraisals under review and on average five times more frequently than other proposals.

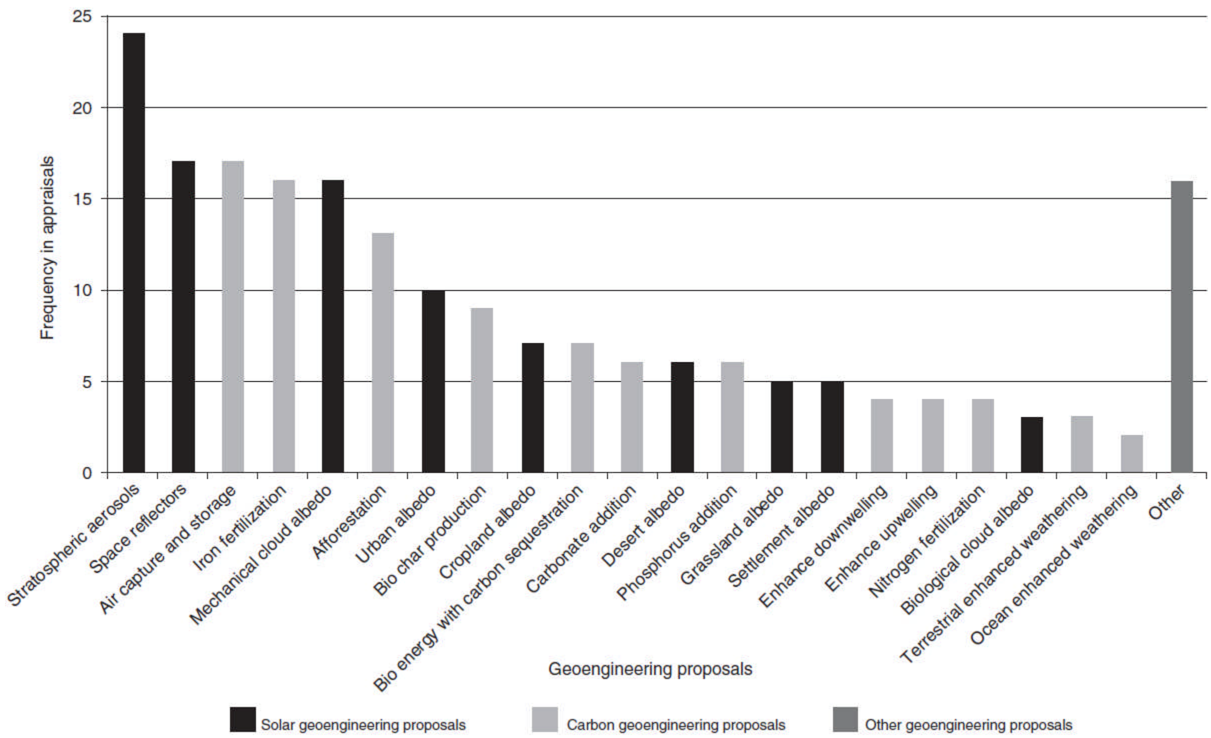


Figure 3.1. Frequency of different geoengineering proposals featured appraisals (updated from Bellamy *et al.*, 2012). 'Other' geoengineering proposals are those only featured once. Supplementary appraisals (i.e. the participatory appraisals undertaken by the Royal Society (2009) and US GAO (2011) in addition to their primary expert-analytic appraisals) are counted here as separate appraisals.

The few exceptions to this contextual isolation appraise geoengineering proposals alongside single courses of mitigation action, including mitigation as a catch-all category (Levi, 2008) or carbon capture and storage (CCS) (Royal Society, 2009); or multiple courses of mitigation action including carbon trading schemes, government regulation, low carbon living, nuclear energy and renewable energy, alongside an option for inaction (Bellamy & Hulme, 2011). These few exceptions aside, geoengineering proposals have thus far been placed in contextual isolation from their alternatives that might be considered under broader problem definitions. This poses an artificial choice between only geoengineering 'options' that restricts and narrows future pathways for responding to climate change.

3.3.2 Appraisal methods and criteria selection

Beyond the construction of problem definitions and contexts lie specific appraisal inputs: methodological choices and criteria selections through which performance of geoengineering proposals is judged. Of the original 21 geoengineering appraisals identified for review an overwhelming majority (18) were identified as expert-analytic in nature (see Table 3.3). Another two were expert-analytic in their principal focus but were supported by minor participatory elements (Royal Society, 2009; US GAO, 2011). That is to say they were conducted exclusively by experts and utilized methods of appraisal that can be construed as relatively constrained, employing technical criteria discussed earlier in Section 3.2.1, and often quantified in their treatment of the issue. These methods ranged from expert reviews and opinions to calculations and computer modelling to economic assessments to multi-criteria analyses. In Chapter 2 it was determined that such reductive-aggregative methods constitute an inadequate response to the post-normal scientific context in which climate change and geoengineering resides (Funtowicz & Ravetz, 1992; 1993), and an inadequate response to the indeterminate uncertainties (Wynne, 1992a) and incertitude (Stirling *et al.*, 2007) that pervades the issue.

Expert reviews and opinions dominate this category of geoengineering appraisals; a proportion that has been noted elsewhere as significantly higher than in related disciplines (Belter & Seidel, 2013). The reviews seek to synthesize disparate existing information (e.g. Vaughan & Lenton, 2011); apply it to a novel context (e.g. Crabbe, 2009) or use it to inform expert opinion (e.g. Izrael *et al.*, 2009). Each of these objectives is capable of closing down the range and quality of appraisal outputs through their inherently selective choice of information for inclusion and exclusion. Where expert opinions are offered the subjective reasonings that underpin them are often under-explained or unaccounted for. For example, the classification of the risk of side effects posed by space reflectors as simply 'low' hides the reasonings that underpin that conclusion (see Keith, 2000). Similarly, the arbitrary ranking of geoengineering proposals according to their supposed feasibility lacks transparency (e.g. Fox & Chapman, 2011).

In a notably different approach to expert review, the US GAO (2011) technology assessment included foresight scenarios to explore future visions of geoengineering research. While this exercise was still constrained to expert opinions only, the assessment constructed four scenarios around which the participants' subjectivities and imaginaries could be exposed and reflected upon. Despite the limited range of scenarios and participants, it represents an important step forward in opening up visions of the range of possible futures in which geoengineering could reside.

Those appraisals employing calculations or computer models are naturally constrained to the disciplinary study of technical criteria. Methodological choices made within these appraisals inevitably involve making contestable assumptions about the futures in which geoengineering would operate. For example, the use of the Bern carbon model in producing CO_2 scenarios assumes that geoengineering would have no impact on the carbon exchange processes between atmosphere, biosphere, and oceans (see Moore *et al.*, 2010). Similarly, the use of strong mitigation or balanced use of energy sources as scenario baselines assumes certain social and technical developments while ignoring other possible futures and sensitivities (see Lenton & Vaughan, 2009; Jones *et al.*, 2011).

Sources of uncertainty in climate models relating to the representation of baseline conditions, forcings, and sensitivities are well documented (Randall *et al.*, 2007), but pose some specific issues for modelling the efficacies and impacts of geoengineering. Atmosphere–ocean general circulation models (AOGCMs) are widely used and considered to provide credible projections of future temperature change at large spatial scales. However, projections made at smaller spatial scales such as for regional precipitation patterns are poor, confounding conclusions made in relation to regional geoengineering impacts such as those by surface albedo changes (e.g. Irvine *et al.*, 2011). Moreover, considerable uncertainties remain such as those pervading the modelling of cloud formation and opacity, confounding conclusions made in relation to specific geoengineering proposals such as cloud albedo enhancement (Jones *et al.*, 2011).

A limited number of economic assessments have been made to appraise geoengineering, seeking to identify the benefits and/or costs of different proposals. Here those methods involve calculating the marginal CO_2-equivalent cost of mitigation (COM) (e.g. NAS, 1992) or cost-benefit analysis (CBA) (e.g. Bickel & Lane, 2009). Critiques of appraisals based solely on economic efficiency criteria are well established, often citing their ignorance of wider issues as well as an inadequate or even inappropriate representation of 'nonmarket goods' (Anderson, 1993). Moreover, economic assessments of novel proposals such as those within geoengineering can more generally suffer from 'appraisal optimism' because of systematic biases in underestimating costs (Flyvjberg *et al.*, 2003).

Economic assessments are especially open to framings with respect to their treatment of sensitivities and the discounting of time. While the CBA conducted by Bickel and Lane (2009) does include a number of different emission controls scenarios as well as market and ethical discount rates, these assumptions are subject to huge uncertainties in the literature. In a demonstration of the powerful effects that these framings can have on appraisal outputs, another CBA using the same dynamic integrated model of climate and the economy (DICE), but different assumptions, was performed that led to quite different conclusions (Goes *et al.*, 2011). Where stratospheric aerosol injection achieved an admirable benefit-cost ratio of 25 to 1 in Bickel and Lane (2009), Goes *et al.* (2011) concluded that the solar geoengineering proposal failed cost-benefit analysis altogether under no less plausible assumptions (see Pielke Jr., 2010).

Multi-criteria analysis (MCA) methods can account for a much broader range of appraisal criteria than CBA or other expert-analytic approaches, but are no less susceptible to framings. The selection and diversity of criteria and weightings is critical, determining the scope of the appraisal and which issues are privileged over others. Both Boyd (2008) and the Royal Society (2009) have conducted MCA appraisals of geoengineering utilising the same, loosely defined technical criteria: effectiveness, affordability, safety and timeliness. Such technical analyses fail to take advantage of the wider range of criteria available, spanning social, political, and ethical considerations amongst others.

The expert multi-criteria assessment conducted for the Royal Society's (2009) seminal report provides a valuable illustration of how framing geoengineering assessment through the selection and elevation of particular criteria can compel outcomes. The assessment utilised four technical criteria with which to evaluate the proposals: effectiveness, affordability, timeliness and safety. In then presenting the performances of the different proposals on a two axis figure, a difficult decision was made with respect to which of the four criteria would be given priority on those axes. It was decided that effectiveness and affordability would be given that normative priority, and under that configuration stratospheric aerosol injection performed the highest overall.

The prioritisation of effectiveness and affordability on those axes, however, was only one of a possible six permutations (see Figure 3.2). Each of the differently framed permutations offers a distinct pattern of performances, where different overall conclusions can be drawn. Where the original configuration places stratospheric aerosol injection most highly (a), that performance is accentuated even further under effectiveness and timeliness criteria (b), owing to its perceived capacity for pre-emptive or responsive action in facing a 'climate emergency'. Where safety is prioritised alongside effectiveness a somewhat different picture emerges (c), with air capture and storage performing the highest overall. Under affordability and timeliness criteria, stratospheric aerosol injection returns to a high performance, but alongside the somewhat more benign afforestation (d). Afforestation retains the coveted position of highest overall performance under affordability and safety, and timeliness and safety criteria (e, f).

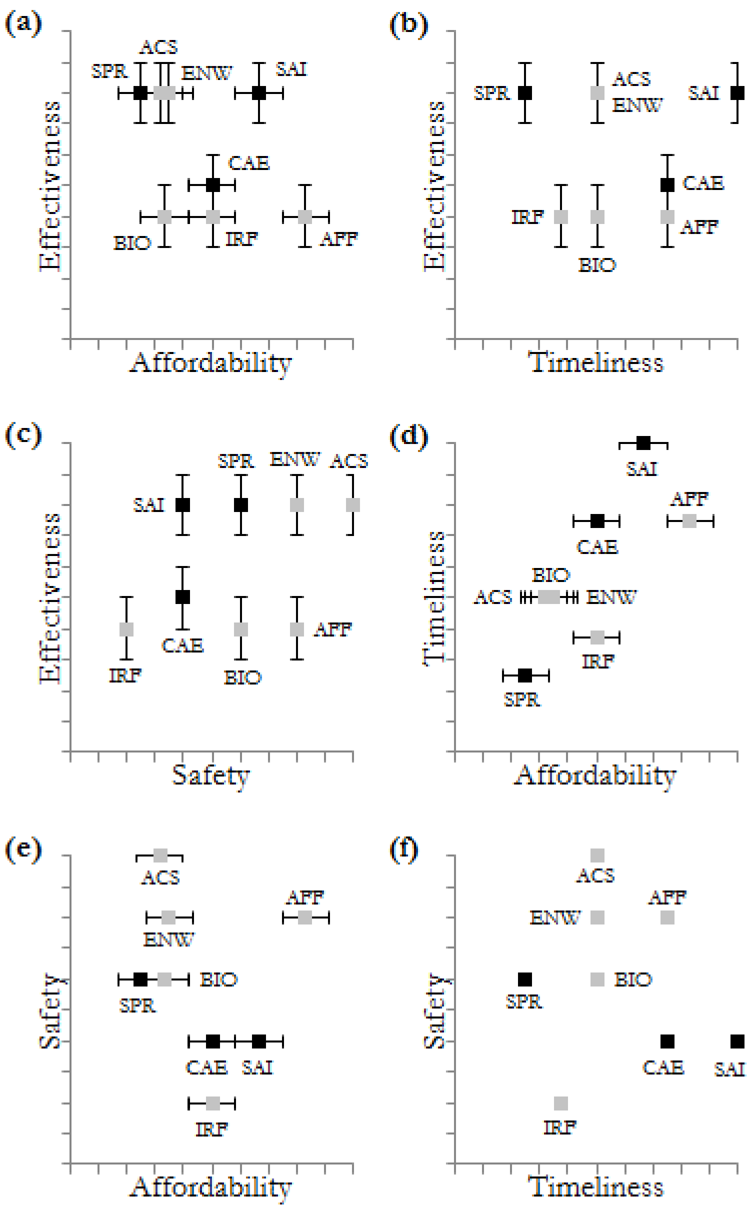


Figure 3.2. Permutations in a multi-criteria assessment of geoengineering proposals. Acronyms: afforestation (AFF); air capture and storage (ACS); biochar (BIO); cloud albedo enhancement (CAE); enhanced weathering (ENW); iron fertilisation (IRF); stratospheric aerosol injection (SAI); space reflectors (SPR). Proposals coloured grey and black represent carbon geoengineering and solar geoengineering proposals respectively. This figure was produced using the original performance scores and margins of error for select proposals provided in the Royal Society (2009).

What else can be observed from the Royal Society MCA is the use of small, arbitrary error bars in relation to the effectiveness and affordability criteria. Whilst no doubt underestimating the true uncertainties that underlie the single mean score, data point option performances, they also hide the full range of scores given by the participating experts, whilst the reasonings underpinning those judgements remain hidden and unaccounted for.

Only one participatory appraisal was identified in the initial search and screen strategy, with four more added after a relaxation of the screening strategy, and a further two following the update of this review. The participatory appraisals of geoengineering can be classified among those employing surveys, focus groups, or deliberative workshops; each seeking to elicit public and/or stakeholder views and perceptions of geoengineering. Surveys were the most common methods in this category of geoengineering appraisals, using a combination of online instruments, telephone interviews, or face-to-face interviews. These most often quantitative methods are constrained by a limited appreciation of the participant reasonings that underpin perceptions. For example, that 72% of people somewhat or strongly support solar geoengineering proposals tells us little of the supportive or confounding influences on that claim (see Mercer *et al.*, 2011). Furthermore, emergent issues such as geoengineering about which the public knows very little are likely to derive 'constructed preferences' rather than public opinion (Slovic, 1995).

Focus groups can offer much deeper explanations of what underpins public understandings and concerns about geoengineering, but are still bound by their choice of focus for discussion. For instance, the Royal Society (2009) sought to elicit the perceived benefits, risks, and uncertainties about geoengineering; Bellamy and Hulme (2011) introduced geoengineering as an option for counteracting climate tipping points, seeking to elicit policy preferences; and the US GAO (2011) sought to elicit reactions to geoengineering proposals, support or opposition, and how to best make decisions about geoengineering in government, industry, and as individuals. The recruitment of participants also constitutes an important framing here. For example, the use of university participants in convenience sampling, an accessible and popular strategy in psychological research, can produce unrepresentative western, educated, industrialized, rich, and democratic ('WEIRD') representations of humanity (see Bellamy & Hulme, 2011; Jones, 2010).

Deliberative methods, including special forms of focus group (e.g. Macnaghten & Szerszynski, 2013) and workshops (e.g. Parkhill & Pidgeon, 2011; Pidgeon *et al.*, 2013; Corner *et al.*, 2013) offer the least constrained methods of eliciting public views on geoengineering. While still employing some focus to direct the deliberations, these methods can allow participants to frame the discussions to some extent themselves and thereby facilitate a deeper exploration of perspectives. However, these methods are just as susceptible to other framings as other appraisal designs, including through the provision of information. As outlined in section 3.3.1 the inadvertent or deliberate introduction of particular frames, such as climate emergency or naturalness frames, can influence the perceived acceptability of geoengineering proposals (see NERC, 2010; Corner *et al.*, 2011). Parkhill & Pidgeon (2011) refer to this as 'treading a fine line' between providing sufficient information for discussion without influencing participants' views.

3.3.3 Reflexivity and output recommendations

The extent to which appraisals of geoengineering acknowledge the myriad of framings bearing upon their outputs is a decisive framing condition in itself. The reflexivity with which those framings are conveyed directly impacts on the legitimacy of any conclusions or recommendations that are drawn from them. Figure 3.3 plots the relative extent to which framings are conveyed in geoengineering appraisal outputs (closing down or opening up) against the relative extent to which those framings act to narrow in or broaden out the appraisal inputs. The four quadrants of the figure show where: (1) inputs are narrow and outputs closed; (2) inputs are narrow but outputs are open; (3) inputs are broad but outputs are closed; and (4) inputs are broad and outputs are open. The majority of the geoengineering appraisals under review were identified as having low levels of reflexivity and occupy quadrant (1). Given the post-normal, highly complex and uncertain nature of climate change and geoengineering, reflexivity should be a central feature of outputs from appraisals that should broaden out their inputs, occupying the currently vacant quadrant (4).

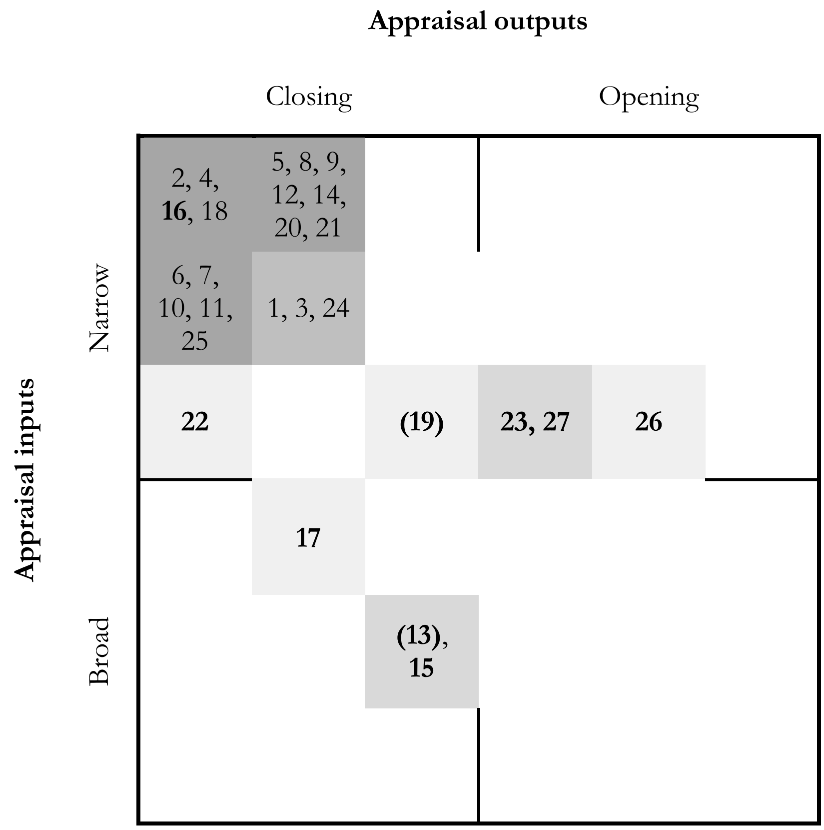


Figure 3.3. Breadth of inputs and openness of outputs in geoengineering appraisals (updated from Bellamy *et al.*, 2012; after Stirling *et al.*, 2007). Bold numbers represent participatory appraisals; bold, bracketed numbers represent expert-participatory appraisals; and plain numbers represent expert-analytic appraisals. Numbers relate to appraisal numbers in Table 3.1 and are in ascending chronological order. Appraisal positions in the grid are necessarily interpretative, and not definitive but indicative. Appraisal breadth was assessed as either low or high in a 2 × 2 matrix in relation to the scope with which appraisals accounted for the character of the decision context and the diversity of relevant knowledges; then positioned relative to one another within a 3 × 3 sub-matrix. Appraisal openness was assessed as either low or high in a 2 × 2 matrix in relation to the reflexivity with which framings are conveyed and outputs made, then positioned relative to one another within a 3 × 3 sub-matrix.

These low levels of reflexivity hide uncertainties and subjectivities that are bound within the framings and result in substantial variability between different appraisals' outputs that relate to the same geoengineering issues. For example, a judgement frequently aired in geoengineering appraisals relates to the risk of side effects. The purported risks of one particular solar geoengineering proposal, space reflectors, for instance, varies wildly from very low (Keith & Dowlatabadi, 1992), to low (Keith, 2000) to moderate (Royal Society, 2009) and to high (Levi, 2008; Irvine & Ridgwell, 2009). Similarly, whilst iron fertilization is viewed as relatively effective by Philip Boyd (Boyd, 2008), it is viewed as relatively ineffective by the Royal Society (Royal Society, 2009).

Ultimately, low reflexivity has amounted to many geoengineering appraisals making unitary and prescriptive recommendations for policy, closing down on particular course(s) of action. Each of the appraisals under review suggests further research is needed, but some go further and produce definitive recommendations as to which geoengineering proposals are the best in different respects or deserve particular attention. Indeed, some go further and recommend funding particular options, such as for cloud albedo enhancement and stratospheric aerosol injection to a prioritised share of $750 million (see Bickel & Lane, 2009). Sections 3.2.1 and 3.2.1 review the range of these findings, where recommendations have been primarily advanced on the basis of technical factors relating to efficacy, feasibility, economics or risk, and to a lesser degree on the supposed basis of social preference. Each of those recommended proposals is ostensibly preferable given the respective framings upon which they are built.

Conclusions

This chapter has undertaken the first systematic review of climate geoengineering appraisals. It has reviewed the findings of those appraisals, including from those employing expert-analytic methods and those employing participatory and deliberative methods. Expert-analytic methods were found to appraise geoengineering against almost exclusively technical issues, spanning those of efficacy, feasibility, economics and risk. Under these issues, certain geoengineering proposals were found to perform more highly, more often than others. In particular, stratospheric aerosol injection performed almost consistently highly against efficacy, feasibility and economic issues, whilst performing relatively poorly under issues of risk. By contrast, the participatory and deliberative methods were found to appraise geoengineering through the elicitation of public attitudes, whereby grounded themes emerged from within the appraisals themselves rather than predetermined issues. Here, both awareness and support for geoengineering is low, but perceptions are proposal-specific, with carbon geoengineering proposals preferred in general over solar proposals, and those that are perceived as 'natural', including afforestation and biochar, preferred overall.

This chapter has also conducted a reflexive critical analysis of geoengineering appraisals with respect to the role of framings in shaping appraisal inputs and outputs, and ultimately, epistemic commitments to particular responses to climate change. In doing so three central findings have emerged that risk epistemic, and premature lock-in to particular future pathways. First, that the appraisals have adopted narrow problem definitions, with two dominant frames: 'insufficient mitigation' and 'climate emergency'. These frames have contributed to a contextual situation of geoengineering apart from mitigation and adaptation alternatives and resulted in the proposals undergoing appraisal in contextual isolation. Second, the methods employed in appraisals of geoengineering are primarily expert-analytic and reductive-aggregative in nature. This does not adequately respond to the post-normal scientific context in which climate change and geoengineering resides by excluding broader stakeholder and public participation. Concurrently it does not adequately respond to the indeterminate uncertainties and incertitude that pervades the issue. Moreover, the criteria employed by such methods are mostly technical, marginalising vital and broader political, social and ethical issues, amongst others. Third, the appraisals have shown low levels of reflexivity in recognising their different framings and often culminated in unitary and prescriptive decision recommendations.

In building a methodological response to the significant and pervasive limitations of existing appraisals of geoengineering, and in considering the theoretical underpinnings of this critique discussed in Chapter 2, a number of key assertions can be made. First, that such a response should adopt a broader problem definition that enables the inclusion of legitimate alternatives to geoengineering, spanning climate change mitigation options and adaptation. Second, that such a response should employ an inclusive, participatory, and integrated analytic-deliberative appraisal methodology that recognises the indeterminate uncertainties and incertitude that bears upon the issue and introduces a diversity perspectives and criteria through a broadening out of its inputs. Third, that such a response should seek to reflexively open up with respect to its framings and yield plural and conditional decision recommendations that do justice to the myriad complexities and uncertainties that permeate climate change and geoengineering. The selection of this response, and details of its design and implementation are outlined in Chapter 4.

Chapter 4

Methodology

In view of the theoretical perspectives on social appraisal reviewed in Chapter 2, and of the significant and pervasive limitations to appraisals of geoengineering identified and discussed in Chapter 3, this chapter introduces and outlines Deliberative Mapping (DM) as a theoretically informed methodological response to geoengineering appraisal design. First, the rationale for the selection of DM as that response is considered together with an overview of the DM process and its framing in Section 4.1. Second, the methodological design of the specialist strand of the process is outlined with respect to participant scoping and recruitment, and the conduct of Multi-Criteria Mapping (MCM) interviews, in Section 4.2. Third, the design of the citizen strand of the process is outlined with respect to participant scoping and recruitment, an online resource website, and the conduct of citizens' panels and a joint citizen-specialist workshop, in Section 4.3. Fourth, the chapter concludes by outlining the quantitative and qualitative methods of analysis in Section 4.4.

4.1 Deliberative Mapping

In this section the rationale for the selection of DM as the theoretically informed methodological response to the limitations to existing appraisals of geoengineering will be outlined in Section 4.1.1. Section 4.1.2 will then provide some background on the purpose and origins of DM as well as an overview of its application in this thesis, followed by an outline of pilot studies performed in advance of conducting the process in Section 4.1.4. The problem definition and context adopted in this application of DM will be introduced and discussed in Section 4.1.3.

4.1.1 Method selection

In Chapter 3, three significant and pervasive limitations to existing appraisals of geoengineering were identified and discussed. These limitations, spanning their adopted problem definitions and contexts, their methods and criteria, and their reflexivity, amount to the erroneous designation of the geoengineering issue as one of 'risk', to be appraised through methods of 'normal' science characterised by low decision stakes, uncertainties and incertitude (Funtowicz & Ravetz, 1992; 1993; Stirling *et al.*, 2007). The appraisals thus neglect the post-normal scientific context in which geoengineering resides and the indeterminate states of uncertainty (Wynne, 1992a), ignorance and ambiguous incertitude. This has led to the employment of narrow framings that close down upon particular knowledges and future pathways, and that are conveyed with low levels of reflexivity outside of a framework for responsible innovation (Stirling, 2008; Owen *et al.*, 2013; Stilgoe *et al.*, 2013).

Methodological responses to these different issues in appraisal design were identified throughout Chapter 2. In identifying these issues an array of criteria for methodological selection were laid down. In these terms, the selected method should be anticipatory, reflexive, inclusive and responsive (situated within broader systems of governance), engaging upstream with publics and stakeholders as well as experts in an analytic-deliberative process, broadening out inputs and opening up outputs. DM, with its two constituent methods, MCM and Stakeholder Decision Analysis (SDA), is arguably the only method that fulfils these criteria. Other candidate methods did not satisfy the need for analytic-deliberative integration, and whilst broadening out appraisal inputs would close down outputs (e.g. consensus conferences) or whilst opening up appraisal outputs would narrow inputs (e.g. Q-method).

4.1.2 Method overview

DM is an analytic-deliberative multi-criteria option appraisal process that engages with diverse experts and stakeholders (specialists) and members of the public (citizens) in the assessment of complex and uncertain issues, such as geoengineering (Davies *et al.*, 2003; Burgess *et al.*, 2004; Burgess *et al.*, 2007). It combines the strengths of the expert-analytic MCM (Stirling, 1997) with those of the participatory-deliberative SDA (Burgess *et al.*, 1988), generating quantitative assessments of option performance and qualitative explorations of the reasonings that underpin such judgements. It is distinctive in that it is the only method that invites specialists and citizens to participate in the same appraisal process. This consistency allows for direct comparisons of convergence and divergence between different sector and group perspectives of those participating in the process. In short,

> *'Deliberative Mapping successfully combines inclusiveness and openness to divergent perspectives; specificity and robustness in its policy implications; transparency and auditability for third parties; and efficiency and added value for sponsoring policy institutions'* (Burgess *et al.*, 2004: 66).

DM was first developed to overcome the well-established limitations of traditional multi-criteria analysis and public and stakeholder engagement methods, much as MCM and SDA were before it. In particular, the process avoids the concealment of variables and proliferation of complexities by adopting the most basic of theoretically valid mathematical methods. This thesis builds upon decades of the successful development and application of DM and its constituent appraisal methods in the anticipatory appraisal of other analogous emerging sciences and technologies including genetically modified (GM) organisms (Stirling & Mayer, 2001), medical transplant technologies (Davies *et al.*, 2003), and energy technologies (Stirling, 1994), as well as more conventional but still complex issues such as managing legacy radioactive waste (Burgess *et al.*, 2004; Chilvers & Burgess, 2008) and forms of environmental planning (Burgess, 2000).

Following the application for and acquisition of ethical clearance for the research through a review by the internal University of East Anglia ethics committee, the DM process took place during the summer and autumn of 2012, comprising two parallel strands of engagement: one for specialists and one for citizens, with the strands converging for interaction in a joint workshop mid-way through the process (see Figure 4.1). The DM process reported here more closely resembles Burgess *et al.* (2004) than Davies *et al.* (2003), with the citizens' strand in particular taking place over a shorter but more intensive period of time. Following an online recruitment survey, the citizens' strand began with a full-day citizens' panel workshop before reconvening several weeks later for a half-day joint workshop with specialists and a second half-day citizens' panel workshop. Following a series of scoping telephone interviews, the specialists' strand began with 1 – 3 hour face-to-face MCM interviews before a second set of 1 – 2 hour MCM interviews several weeks later, after the joint workshop with citizens.

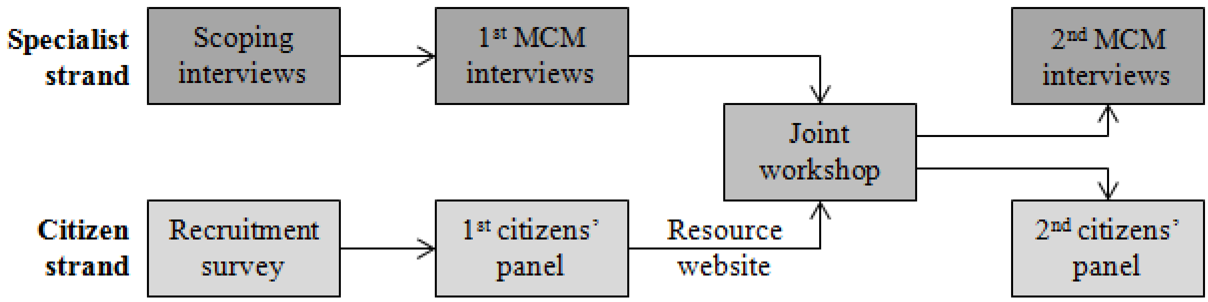


Figure 4.1. Overview of the Deliberative Mapping process.

Much as with other multi-criteria appraisal methods, the DM process comprises four stages: (1) developing a set of options to appraise; (2) characterising a range of criteria against which to assess those options; (3) scoring the relative performance of the options against those criteria; and (4) assigning a weighting to each criterion to indicate their relative importance. Both of the strands followed these same four stages, albeit through different mediums.

4.1.3 Pilots

Pilot studies of the first MCM interviews and first and second citizens' panels were performed prior to conducting the DM process, with peer volunteers at the University of East Anglia. As the 'core' components of the process it was important to test their different protocols' contents and timings, as well as familiar and non-familiar participant engagement with the issues under consideration. Indeed, the pilots did compel a number of refinements to the protocols, primarily in relation to allowing enough time for the satisfactory completion of each phase of the appraisal. The pilot studies also provided the author with the opportunity to rehearse the facilitation of both one-to-one and group discussions and conduct operational testing of the audio recording equipment and the Multi-Criteria Mapper computer software.

Importantly, the pilot studies allowed for the testing of option resolution with participants. At first, six core options were presented at very high levels of aggregation consisting of two mitigation option groups, two geoengineering proposal groups, and two adaptation strategy groups: (1) energy conservation and efficiency; (2) low carbon energy; (3) carbon geoengineering; (4) solar geoengineering; (5) anticipatory adaptation; (6) reactive adaptation. Such high levels of aggregation proved difficult for participants to engage with, where in considering one option (e.g. carbon geoengineering), manifold sub-options would compete for attention (e.g. afforestation, air capture and storage, iron fertilisation) and result in a proliferation of complexity where certain options would dominate and others were forgotten. Such an appraisal led to participants appraising different options, undermining the imperative for 'common' options between participants. Options were subsequently restricted to a clearly definable and discrete resolution, developed through consultation with the project team and the specialist participants, which through further pilot testing proved practicable.

4.1.4 Framing

In recognising the narrow contextual limitations of earlier appraisals of geoengineering identified in Chapter 3, this study adopted an open problem framing and broad decision context. Rather than defining the 'problem' as a leading one of 'insufficient mitigation' or the risk of a 'climate emergency', for example, it was framed as an exercise in 'responding to [global] climate change' which allowed for a diversity of perspectives to bear upon it. This problem framing extended to the adopted decision context, where geoengineering proposals were presented alongside alternative options for responding to climate change; as well as allowing for the introduction of additional options defined by the participants themselves.

Options for responding to climate change can be broadly divided amongst mitigation, adaptation and geoengineering strategies. The Intergovernmental Panel on Climate Change (IPCC) defines mitigation as *'implementing policies to reduce greenhouse gas emissions and enhance sinks'* (IPCC, 2007: 84). The inclusion of sink enhancement in this definition reflects some ambiguity relating to the categorisation of carbon geoengineering proposals, some of which share this aim. In this study they are disaggregated, restricting mitigation to mean options available to reduce greenhouse gas emissions, spanning energy conservation and efficiency and low carbon energy production.

The IPCC defines adaptation as *'…measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects'* (IPCC, 2007: 76). The objectives of adaptation, however, are fundamentally different to those of geoengineering and mitigation. Whilst those latter strategies seek to avoid or lessen climate change itself, adaptation seeks to address its impacts. Adaptation comprises options that are responses to temporally and spatially specific impacts, experienced as weather events, and thus cannot be presented alongside geoengineering and mitigation options at a meaningful resolution. For example, stratospheric aerosol injection and offshore wind energy both seek to tackle or avoid climate change, but constructing flood defences does not. Whilst adaptation strategies could not be meaningfully included in the study as discrete options to appraise, the concept of adaptation and of adaptive capacities would be implicitly addressed through the inclusion of a baseline 'business as usual' option and its resultant climatic impacts.

In light of the pilot studies, a review of options for responding to climate change yielded an extensive range of discrete potential options for inclusion within the study (see Appendix 1.1.1 for a summary of the options review). For practical reasons these options could not be presented for appraisal in their entirety, and so the options were screened against a range of criteria in order to produce a list of discrete options to appraise that were indicative of the diversity of options available. These criteria judged the diversity of: (1) strategies (geoengineering or mitigation, technological or non-technological, engineered or natural); (2) likely governance (territorial or commons-based operation, centralised or distributed control); (3) policy instruments (regulatory, market-based or voluntary); and (4) novelty and maturity (novel and immature or established and mature). The review yielded seven 'core' options, ordered in terms of likely familiarity, to be appraised by all participants in the study and seven 'discretionary' options to be appraised by participants at their discretion (see Table 4.1) (also see Appendices 1.1.2 and 1.1.3 for the option booklets). Options were necessarily presented at different scales of impact and none were presented as 'silver bullets' capable of tackling climate change in isolation.

Table 4.1. The definitions of 'core' options (C1 – C7) appraised by all participants and 'discretionary' options (D1 – D7) appraised by some participants at their discretion.

Option	Definition
C1 Voluntary low carbon living	Promoting voluntary reductions in domestic and commercial energy use.
C2 Offshore wind energy	Increasing the proportion of energy provided by offshore wind turbines.
C3 New market mechanism	Developing a new and expanded market-based carbon trading mechanism.
C4 Biochar	Focusing research and development into the production of biochar and its application to soils.
C5 Air capture and storage	Focusing research and development into the use of technology for capturing CO_2 from the ambient air.
C6 Stratospheric aerosol injection	Focusing research and development into the injection of reflective sulphate particles into the stratosphere.
C7 Business as usual	Continuing with business as usual, with no further adoption of options for responding to climate change.
D1 Nuclear fission energy	Increasing the proportion of energy provided by nuclear fission power stations.
D2 Coal energy with CCS	Focusing research and development into the use of technology for capturing CO_2 at source from coal power stations.
D3 Carbon tax	Increasing and widening taxation of CO_2 emitted during the fuel cycle.
D4 Nuclear fusion energy	Focusing research and development into the use of nuclear fusion for energy generation.
D5 Iron fertilisation	Focusing research and development into the application of iron to the ocean to stimulate algal growth.
D6 Cloud albedo enhancement	Focusing research and development into the use of technology to enhance cloud reflectivity.
D7 Space reflectors	Focusing research and development into the use of reflective mirrors in Earth orbit.

Acronyms: carbon capture and storage (CCS).

4.2 The Specialist Strand

The procedural methods of MCM are explained more fully in, for example, Stirling and Mayer (2001), but aspects specific to this study demand detailed discussion here. In this section the initial scoping for the recruitment of specialist participants is outlined in Section 4.2.1. Section 4.2.2 will then outline the procedures undertaken during the first and second MCM interviews.

4.2.1 Specialist scoping and recruitment

A diverse group of twenty-four specialists and stakeholders were identified by the research team to participate in a series of scoping interviews. Interviewees were identified for their seniority and appreciation of the international context of climate change, and their diversity of perspectives in relation to their: (1) working sector (academia, civil society, industry or government); (2) disciplinary specialism's (natural or social science perspectives relating to general or specific geoengineering proposals or mitigation options); and (3) personal attitudes to geoengineering research (arguments pro or contra geoengineering research as mapped by Betz & Cacean [2012]). Interviewees were screened against these criteria in additional depth during short telephone interviews (see Appendix 1.2.1 for telephone interview protocol), culminating in the recruitment of twelve diverse specialists and stakeholders who would go on to participate in the full MCM study (see Table 4.2).

Table 4.2. The specialist participants.

Code	Position	Expertise	Perspective†
A	Environmental social scientist	M	A9(-); A73(-)
B	Interdisciplinary climate scientist	M, A, G	A32(+); A52(-); A58(-); A75(-)‡
C	Earth system scientist	G	A32(+); A87(+)
D	Science and technology social scientist	G	A32(+)
E	Volcanologist	G	A32(+); A87(+)
F	Int. conservation charity manager	M, G	A32(+)
G	Int. technology action group manager	G	A9(-); A73(-)
H	Int. commercial competition manager	G	A32(+)
I	Nat. engineering institution manager	M, G	A32(+)
J	Nat. government civil servant	G	A32(+); A87(+)
K	Local government public sector officer	M, A	A32(+)
L	Nat. government scientific advisor	M, A, G	A32(+); A87(+)

Acronyms: international (Int.); national (Nat.); mitigation (M); adaptation (A); geoengineering (G). † indicates a participant's perspective on geoengineering research elicited during scoping interviews. Perspectives coded against argument map by Betz & Cacean (2012). Arguments denoted as pro (+) or contra (-) geoengineering research: mitigation obstruction (A9); insufficient mitigation (A32); irreducible uncertainty (A52); socio-political uncertainty (A58); technical fix (A73); hubris (A75); preparing informed decision (A87). ‡ Participant B pro researching select carbon geoengineering proposals complementary to mitigation, contra large scale solar geoengineering.

A thirteenth specialist participant from an industrial working sector, with vested interests in one particular solar geoengineering proposal, cloud albedo enhancement, withdrew from the process early during their first MCM interview. Despite additional explanation and reassurances from the author regarding the qualitative qualifications of quantitative scoring, the participant expressed concerns about a perceived 'compression' and 'distortion' of information into numerical form. These numbers, the participant argued, would be taken as 'facts' and 'misused' by politicians, much as they had apparently been in the Royal Society (2009) assessment.

4.2.2 Multi-Criteria Mapping interviews

Prior to interview participants were given a booklet detailing the aims and methods of the study, together with definitions of the 'core' and 'discretionary' options to be appraised (see Appendix 1.1.2 for specialist participant briefing material and Appendix 1.2.4 for participant consent form). Participants were then interviewed on a one-to-one basis at their place of work using the computer software program 'Multi-Criteria Mapper'. Each participant was guided through the four stage multi-criteria process detailed in Section 4.1.2, in interviews that each lasted between one and three hours (see Appendix 1.3.1 for first MCM interview protocol). A second set of interviews took place several weeks later, following the joint workshop with citizens (detailed in Section 4.3.3), in order to present specialist participants with the initial results of the study, elicit any changes to appraisals and to conduct a 'foresight' exercise in which to explore their views in relation to the possible futures of geoengineering research and development, and its appraisal and governance, as well as to reflect on their participation in the study (see Appendix 1.3.2 for the second MCM interview protocol).

4.3 The Citizen Strand

The procedural methods of the citizens panels are explained more fully in Davies *et al.* (2003), Burgess *et al.* (2004) and Burgess *et al.* (2007), but aspects specific to this study demand detailed discussion here. In this section the initial scoping for the recruitment of citizen participants is outlined in Section 4.3.1. Section 4.3.2 will then outline the procedures undertaken during the first citizens' panel and the provision of information in the online resource website. The joint workshop with specialists and the subsequent second citizens' panel will be outlined in Section 4.3.3.

4.3.1 Citizen scoping and recruitment

A diverse group of thirteen citizens from the Norfolk (UK) public were recruited from respondents to a 'topic blind' online survey about 'global environmental challenges' administered through the Norfolk County Council 'Your Voice' online scheme (see Appendix 1.2.2 for the online survey protocol). The survey accrued information on each respondent's (1) age group and (2) National Statistics Socio–economic Classification (NS–SEC), to ensure sociodemographic representation for the county of Norfolk; (3) gender, to ensure equal representation of sexes (see Appendix 1.2.3 for items 1 - 3 apportionment); and (4) perceived global issue of most concern, (5) favoured strategy for tackling global environmental issues, given recognized cultural preferences (Bellamy & Hulme, 2011), and (6) perceived cause of climate change, to ensure a diversity of perspectives (see Table 4.3). Respondents with environmental 'expertise' were excluded from recruitment, owing to such expertise gaining representation through the stakeholders in the specialist strand of the process. Each participant received an honorarium for their participation in the citizens' panels and the joint workshop.

Table 4.3. The citizen participants.

Code	Age	M/F	NS–SEC	Issue of concern	Strategy†	Climate attribute‡
P1	18 – 24	F	1 – 3	Economic downturn	H	●○
P2	25 – 44	M	1 – 3	Economic downturn	I	○
P3	25 – 44	F	1 – 3	World population	E	●
P4	25 – 44	M	4 – 9	World population	E	●○
P5	45 – 64	M	1 – 3	Climate change	I	●
P6	45 – 64	F	1 – 3	Climate change	E	●○
P7	45 – 64	M	4 – 9	World population	E	●
P8*	45 – 64	F	4 – 9	Climate change	E	●○
P9	65+	M	1 – 3	Armed conflicts	E	○
P10	65+	F	1 – 3	World population	H	●
P11	65+	M	4 – 9	Climate change	E	●
P12	65+	M	4 – 9	Climate change	E	●○
P13	65+	F	4 – 9	World population	E	●○

† indicates strategy refers to preferred strategy for tackling global environmental issues where H indicates hierarchy (expert–led strategy), I indicates individualism (market–led strategy) and E indicates egalitarianism (collective–led strategy). ‡ climate attribute refers to participants' perceived causes of climate change, where ● indicates mainly anthropogenic, ○ indicates mainly natural and ●○ indicates partly anthropogenic and partly natural. * indicates participant only attended the first citizens' panel due to illness during the second.

Fourteen citizens were initially sought and invited for their participation in the research, with one withdrawing a few days ahead of the first citizens' panel (18 - 24, M, NS-SEC 4 - 9) and one withdrawing some hours ahead (45 - 64, F, NS-SEC 4 - 9). With limited time before the panel, the former participant was replaced, albeit with one of a different age and socioeconomic group (65+, M, NS-SEC 1 - 3). One participant attended the first citizens' panel but was unable to attend the second due to illness (P8).

4.3.2 First citizens' panel and resource website

The citizens began their engagement with the first citizens' panel which happened over the course of one full day at the Yours Business Networks conference venue in King's Lynn, Norfolk, and was facilitated by the author and Dr. Jason Chilvers (see Appendix 1.3.3 for the first citizens' panel protocol and Appendix 1.2.4 for participant consent form). Throughout both panels the citizens would be divided into two groups by gender, for reasons of established theoretical and observational evidence of differing risk perceptions and assessments (Gustafson, 1998) and of differing engagements and difficulties with the process (Davies *et al.*, 2003). Indeed, the working environments in the two groups proceeded to be quite different, with the men's group undertaking somewhat more adversarial interactions, whilst the women's group undertook more consensual interactions. These forms of interaction were later reflected in the option scoring process, where more divergence could be observed in the men's group scores.

The first citizens' panel was divided into several sessions: (1) openly framed group discussions of global environmental issues advanced through climate change to options for tackling climate change; (2) an overview presentation of climate change, its impacts and mitigation, adaptation and geoengineering responses, and the core and discretionary options under consideration, followed by plenary discussion; (3) group discussions exploring options followed by poster viewing of options under consideration; (4) individual, paired and then group development of criteria for appraisal through negotiated amalgamation, followed by plenary discussion to agree a common set of criteria across both groups; and (5) preparation for the joint workshop with specialists.

In preparation for the joint workshop citizens were asked to consider questions for the attending specialists. Further to this, citizens were asked to undertake 'homework' research into the issue and the options under consideration. Printed option booklets (see Appendix 1.1.3) and a purpose-built resource and debate website were made available to direct their research in between panels and provide an online space for further participant deliberation (globalenvironmentalchallenges.wordpress.com). A range of media, government and academic resources covering climate change and its impacts, as well as geoengineering proposals and mitigation options, were included. Five participants proceeded to utilise the 'discussion' feature of the website, with questions and opinions centring around low carbon energy options and the politics of climate change.

4.3.3 Joint workshop and second citizens' panel

The joint workshop occurred several weeks later and took place over the course of half a day at the University of East Anglia. In this component of the strand, citizens reviewed their homework research into the options before partaking in and reviewing a joint citizen-specialist workshop (see Appendix 1.3.4 for the joint workshop protocol). In this session citizens were divided into three mixed groups of four and were instructed to visit the two specialists present (the volcanologist and international conservation charity manager) and the author (who broadly introduced the perspectives of the remaining specialists who were unable to attend) at three separate tables around the room. The participants proceeded to question and challenge the specialists about their perspectives and about the options under consideration, in such a way that would inform their later appraisal of the options. This was done with groups rotating approximately every fifteen minutes, much like the 'specialist fair' undertaken in Davies *et al.* (2003) and was followed by a review session where specialists and citizens reflected on their learning.

The second citizens' panel took place over the remaining half day immediately after the joint workshop (see Appendix 1.3.4 for the second citizens' panel protocol). In this final component the citizens scored the relative performances of the options under consideration (see Appendix 1.3.5 for an example of the scoring sheets) and assigned weightings to their criteria, before reflecting on their participation in the overall DM process. The scoring of options and weighting of criteria was a novel feature of the present DM research. In other DM processes, citizens assigned a single score of option performance for each option under each criterion, from which the range of variability between the highest and lowest single scores would be derived. Here, uncertainty was measured as distinct to variability with citizens invited to use the same optimistic and pessimistic scoring method as the specialist participants. With respect to the weighting of criteria, rather than conducting a discursive group elicitation of relative importance as in other DM processes, individual citizens assigned their own weightings in much the same way as the specialists did in their strand. These features were included with the objective of developing individual citizen participant option rankings with uncertainty ranges rather than group rankings with variability ranges.

Citizen engagement with these new features were received with mixed enthusiasm. Whilst the new weighting regime was conducted with no issue, the new scoring regime was less successful with half (six) of the citizens opting to use the two scores and only two (P5 and P6) opting to use them widely. The resultant analyses of individual citizen rankings are therefore comparatively more 'certain' than those appraisals by specialists, albeit to a lesser degree than those of previous DM processes. However, given the limited uptake of this approach to scoring, as well as the recorded use of 'middle' scores by some participants to represent uncertainty instead, the subsequent analyses also focus on the range between the highest and lowest single citizens' scores on given options.

4.4 Analytical Methods

The DM process produced a wealth of quantitative and qualitative data from each strand that were analysed in accordance with the procedures outlined in Burgess *et al.* (2007). In this section the different quantitative and qualitative methods of analysis are outlined in Sections 4.4.1 and 4.4.2 respectively.

4.4.1 Quantitative analytical methods

The DM process produced a variety of quantitative and qualitative data outputs. The quantitative data consisted of 'optimistic' and 'pessimistic' scores of option performance given by each specialist participant and some citizen participants, or individual scores by others (taken together as a quantification of uncertainty or variability respectively), and criteria weightings. These data allowed for the production of aggregate scores of option performance rank, calculated using a simple linear additive weighting aggregation model (see Equation 4.1):

$$R_i = \Sigma_c S_{ic} \cdot W_c \qquad [4.1]$$

where overall performance rank for a given option (R_i) is the sum of performance scores for that option under a given criterion (S_{ic}), multiplied by the corresponding criterion weighting (W_c) (see Stirling & Mayer, 1999).

A 'real-time' sensitivity analysis was performed during the interview to assess the effects of different criteria weightings on overall option rankings. Each participant concluded with satisfaction that their chosen weightings accurately represented their perspectives. A second sensitivity analysis was conducted to assess the effects of ranking aggregate optimistic and pessimistic scores on overall rank order, which were found to change very little.

4.4.2 Qualitative analytical methods

The DM process also produced in-depth qualitative data of the key reasonings, meanings and considerations of all participants in relation to: the overall framing of the problem and options for responding to climate change; the criteria and principles against which the performance of options was judged; the judgements made in scoring the options against criteria; weighting considerations; and reflections on the appraisal process and implications for geoengineering governance. All interviews were audio recorded, fully transcribed (see Appendices 2.1.1 and 2.1.2 for example transcripts from the specialist interviews and citizens panels respectively) and subject to 'open coding' analysis (Strauss & Corbin, 1990) using the qualitative data analysis software program NVivo 9. As part of this process criteria and principles were coded first into emergent sub-groups of related issues, and second into emergent overall groups of related sub-groups. The reasonings underpinning judgements of option performance against each criterion were then explored in the analysis.

Chapter 5

Specialist Strand Results and Discussion

This chapter is the first of two dedicated to the analysis and discussion of the results of the Deliberative Mapping (DM) process with reference to the wider literature. In this chapter the results of the specialist strand, composed of experts and stakeholders who participated in the first and second Multi-Criteria Mapping (MCM) interviews, are presented. First, the participant-defined 'additional' options are reported, together with the appraisal criteria developed by specialist participants with which to evaluate those options alongside the core and discretionary options, in Section 5.1. Second, the qualitative performance of different geoengineering and mitigation options and business as usual, is reported with respect to different groups of criteria in Section 5.2. Third, the relative weighted importance of different criteria are reported together with the overall option rankings. The chapter concludes by summarising its substantive contributions to knowledge and considering their implications.

5.1 Options and Criteria

The specialist participants developed a range of additional options to appraise alongside the core and discretionary options, as well as a rich diversity of criteria with which to evaluate them. These additional options and criteria are considered respectively in Sections 5.1.1 and 5.1.2 below.

5.1.1 Additional options

In addition to the seven core options detailed in Section 4.1.4 , ten specialist participants opted to appraise discretionary options (also see Section 4.1.4), with two appraising all seven of them. Iron fertilisation was selected for appraisal by five specialists, with cloud albedo enhancement and a carbon tax selected by four specialists each. The remaining discretionary options were selected for appraisal by three specialists each. Seven specialists also introduced a total of nine 'additional' self-defined options, either as openly favoured options, cases of particular interest, or simply to fill perceived gaps in the list of core and discretionary options (see Table 5.1). Four of these were carbon geoengineering proposals (A6 - A9), two of which were variants of air capture and storage (A7 - A8). Another four were approaches to mitigation (A1 - A4), and one was a broader 'cultural transformation' (A5), to which responding to climate change was considered a co-benefit.

Table 5.1. The definitions of 'additional' options (A1 - A9) defined and appraised by specialist participants.

Option	Definition
A1 Agricultural emissions reduction (L)	Developing an international framework to reduce deforestation and CO_2 emissions from agriculture.
A2 End-use efficiency enhancement (L)	Focusing research and development into increasing the end-use efficiency in the building and transportation sectors.
A3 Low carbon R&D (D)	Focusing investment in research and development for low carbon technologies in general.
A4 National policy framework (F)	Developing an international framework to reduce CO_2 emissions within which national governments set policy through regulation and subsidies.
A5 Cultural transformation (B)	Culturally redefining 'growth' from GDP and consumption to indicators of wellbeing.
A6 Afforestation (E)	Increasing the proportion of the Earth's land surface covered by forests.
A7 Closed-loop air capture (I)	Focusing research and development into the use of technology for capturing CO_2 from the ambient air, then developing fuel from the captured gas through air fuel synthesis.
A8 Air capture set carbon price (I)	Focusing research and development into the use of technology for capturing CO_2 from the ambient air and using the cost incurred to set the carbon price of a new market mechanism and carbon tax.
A9 Enhanced weathering (C)	Focusing research and development into the dissolution of carbonate and silicate minerals and their application to terrestrial or oceanic systems.

Acronyms: gross domestic product (GDP); research and development (R&D). Specialist participant codes of those defining the corresponding additional options are indicated in brackets to the right (see Table 4.2 in Section 4.2.1 for participant codes).

5.1.2 Criteria groups

The specialist participants developed a rich diversity of criteria to appraise options for responding to climate change. A total of 61 criteria were developed, which have been coded into 29 emergent subgroups that form part of 8 main criteria groups (see Table 5.2) (also see Appendix 2.2.1). The criteria developed in interviews addressed issues spanning, and often transcending, the natural, applied and social sciences, ranging from issues of efficacy and environment, to issues of feasibility and economics, to issues of politics, society and ethics. Whilst the criteria may appear discrete, the specialists recognised that each of their criteria represented a complex aggregation of issues and often bore close relations to other criteria. Interestingly, none of the specialist participants developed a set of criteria involving all eight criteria groups.

Table 5.2. Classification of appraisal criteria and principles into groups and subgroups (adapted from Bellamy *et al.*, 2013).

Groups	Subgroups
Efficacy	Climate change impacts reduction†; climatic response time†; efficacy of intended effects; global temperature reduction†; greenhouse gas reduction†
Environmental	Environmental impacts†; environmental side effects†; transboundary impacts†
Feasibility	Development time; state of knowledge; technical feasibility†; resource availability
Economic	Commercial viability; cost†; cost effectiveness; economic sustainability; public investment
Political	Political acceptability†; political viability; governance‡
Social	Cultural acceptability; human impacts‡; social acceptability†; socioeconomic impacts†
Ethical	Distributive justice†; ethical questions; intergenerational equity‡; ownership and control†
Other	Co-benefits†

All listed subgroups are criteria except where: † indicates that the corresponding criterion was also used as a principle; and ‡ indicates a principle. In cases where a criterion overlapped with another, the aspect emphasised during the interview was used to categorise the criterion.

One specialist participant (I) developed their set of criteria in a particularly distinctive style, explaining that they should act as ‘stage-gates’. With explicit reference to the established research and development mechanism of the same name (see Cooper, 1990), they outlined how options should first be assessed in terms of their practical feasibility; and if they proved viable they would be permitted to progress to a second ‘gate’ which would assess their environmental risks; and if they proved safe they would be permitted to final gate which would assess their sustainability and legacy. This concept found resonance with the MCM notion of ‘principles’, against which options could be deemed acceptable or unacceptable and ruled in or out accordingly. A total of 23 principles were developed and subsequently classified into 18 emergent subgroups which map onto the same 8 groups of the criteria (see Table 5.2). 15 of the subgroups were developed initially as criteria but later repeated as separate principles to rule out options deemed unacceptable. The remaining 3 were developed purely as principles, regarding issues of governance, human impacts and intergenerational equity.

5.2 Option Scoring

The MCM interview transcript datasets revealed a wealth of in-depth qualitative reasonings that underpinned the specialist participants' scoring of option performance. These reasonings are discussed with reference to other literature in this section and are organised around the eight criteria groups in Sections 5.2.1 – 5.2.8. Therein the performance of each of the core, discretionary and additional geoengineering and mitigation options and business as usual is discussed respectively in further subsections (e.g. 5.2.1.1 – 5.2.1.3). It should be noted that the scores of discretionary and additional options are not directly comparable, having been scored by different or single participants only respectively. Overall option scoring against the criteria groups is outlined according to the rank means for corresponding criteria, and to variability between specialist perspectives (or uncertainty between optimistic and pessimistic scores for additional options appraised by sole specialists) determined by the rank extrema for corresponding criteria (see Appendix 2.3.1).

5.2.1 Efficacy

The scores of option performance against efficacy criteria bore a close relationship with issues of feasibility. Options were often scored under caveats of the extent to which specialist participants believed an option would work effectively or be adopted.

5.2.1.1 The efficacy of different geoengineering proposals

Of the core geoengineering options, the efficacy of **stratospheric aerosol injection** was the most variable. This was in part a reflection of what specialist participants' deemed to be the 'objective' at stake, be it temperature reduction, greenhouse gas reduction or otherwise, culminating in a variety of different efficacy criteria. Specialists concerned with a reduction in global temperature (A, E, K, L) or a rapid climatic response time (E) scored the option very highly, with one specialist describing it as 'very easy actually, alarmingly easy, to see a reduction in global temperature that you want' (E). The high scores were accompanied by caveats relating to potential difficulties in achieving globally uniform temperature changes. Unsurprisingly, specialists concerned with a reduction in greenhouse gases (B, G, J) scored the option very poorly, citing the option's failure to address CO_2 emissions or atmospheric concentration and the associated problem of ocean acidification. The option was ruled out against efficacy principles by Specialists A and G. This variability is in stark contrast with other appraisals' consistent claims of high efficacy (e.g. Izrael *et al.*, 2009; Lenton & Vaughan, 2009; Royal Society, 2009).

The efficacy of **air capture and storage** was also highly variable, but it scored moderately overall. Whilst specialist participants expressed confidence in people's willingness to invest in the technology, much of the uncertainty stemmed from its perceived technological immaturity. Specialists cited its feasibility in principle, but raised doubts as to its potential performance at scale owing to resource limitations for processing vast quantities of air and the availability of geological reservoirs for its storage aspect. The option's slow rate of effect and failure to address other greenhouse gases were also cited. These findings too contrast with the high performance rating given by the Royal Society (2009). **Biochar** performed poorly against efficacy criteria, with many specialists citing significant resource and spatial limits to its potential scalability, affirming constraints reported elsewhere (e.g. Royal Society, 2009).

Of the discretionary geoengineering options, **cloud albedo enhancement** performed most highly, scoring moderately overall but with a high degree of variability. Whilst it was noted that 'It has the capacity to be as good as sulphate aerosols' (E) it was viewed as likely to have a slower climatic response time and less of an effect on global temperature owing to its local scale. On this basis it was seen as potentially useful in 'protecting key areas like [coral] reefs' (F). The efficacy of **space reflectors** was also highly variable, but it too scored moderately. Its climatic response time and capacity for temperature reduction was seen as 'analogous to stratospheric injection' (E), reaffirming research into the options' radiative forcing potential (Lenton & Vaughan, 2009), but it scored poorly in relation to its capacity for tackling additional impacts of climate change such as ocean acidification. **Iron fertilisation** performed very poorly against efficacy criteria, with little variability. This perhaps reflects the highly uncertain and much debated evidence of efficacy in the literature (e.g. Boyd *et al.*, 2007; Smetacek & Naqvi, 2008). The following comment was typical:

> 'Even if you doubled global primary production in the oceans, I don't think you would achieve more than one gigaton of sequestration' (C).

Of the additional geoengineering options, **enhanced weathering** performed moderately against efficacy criteria with a moderate degree of uncertainty. Its seemingly large potential was viewed as limited by the acquisition and processing of the minerals required for terrestrial or oceanic application, reflecting concerns raised elsewhere (e.g. Kheshgi, 1995). **Afforestation** scored poorly and with little uncertainty owing to its slow rate of effect, despite more optimistic assessments elsewhere in the literature (e.g. Canadell & Raupach, 2008).

5.2.1.2 The efficacy of different mitigation options

Of the core mitigation options, the efficacy of a **new market mechanism** was the most variable. Often drawing on their experiences of existing carbon trading market mechanisms, including the European Union Emissions Trading System (EU ETS), specialist participants showed a polarisation of views ranging from extreme optimism to extreme pessimism. Whilst generally seen to perform very highly under the assumption that it were successfully implemented through a global international agreement, the perceived likelihood of such an agreement being achieved coupled with an undervalued carbon price and high emissions quotas led to the option also scoring poorly. Specialist G viewed the option's potential to reduce greenhouse gas concentrations so poorly as to rule it out on principle.

Offshore wind energy performed moderately, with relatively little variability. Although it was emphasised by specialist participants that none of the options under scrutiny should be viewed as a panacea, it was often stated with particular attention to offshore wind energy. Its heterogeneous geographical potential, inherent intermittency of electricity supply and need for effective integration with a 'smart grid' were cited as key limitations to its reliability. The **voluntary low carbon living** option performed very poorly, with some variability in specialists' scores relating to varying degrees of optimism towards its scale of adoption. Its acute susceptibility to the 'collective action problem', the desire of people to maintain carbon intensive lifestyles, and different priorities of both individuals and nations were also cited. The potential efficacy of the option was seen to be highly unlikely, without 'regulation' (L) or a 'disaster' to prompt changes in behaviour (D).

Of the discretionary mitigation options, a **carbon tax** performed most highly, scoring moderately with a large range of variability owing to the propriety of the price of carbon and the different ways in which it might be implemented. **Nuclear fusion energy** also performed moderately with a large range of variability. Described as a promising a 'utopia' by Specialist B, it was concurrently viewed as unlikely to be as effective as it has been portrayed, or unattainable within a timeframe meaningful for tackling climate change. Despite its operational status **nuclear fission energy** performed poorly compared with its fusion counterpart, with a moderate degree of variability owing to perceived limited global uptake and the carbon intensive construction of its power stations. **Coal energy with carbon capture and storage** (CCS) also scored poorly with a moderate degree of variability. Whilst viewed as only offering a small contribution at a global scale, it was seen favourably for allowing the continued use of coal without the release of up to 90% further CO_2 (IPCC, 2005).

Of the additional mitigation options, a **national policy framework** scored most highly with some uncertainty associated with the likelihood of reaching a global agreement and its implementation at national level. Investment in **low carbon R&D** also scored highly with some uncertainty associated with the 'uncertainties and unpredictability's of innovation' (D) and the possibility of both good and bad outcomes. A **cultural transformation** scored moderately with little uncertainty. It was viewed as being capable of removing 'some of the underlying drivers for energy expansion' (B) but that energy demand, especially in developing nations, would still exist and increase. **End-use efficiency enhancement** scored poorly with some uncertainty associated with the likely level of uptake. An **agricultural emissions reduction** scored very poorly, with little uncertainty owing to conflicts with food production demands and associated deforestation.

5.2.1.3 The efficacy of business as usual

Business as usual performed consistently very badly, with Specialists E, F, G and J ruling the option out on principle for its slow rate of mitigation action, if any, and its failure to reduce greenhouse gas concentrations, global temperature and the impacts of climate change.

5.2.2 Environment

5.2.2.1 The environmental impacts of different geoengineering proposals

Of the core geoengineering options, **biochar** scored the most highly against environmental criteria, reaffirming other assessments (e.g. Gaunt & Lehmann, 2008). Whilst some variability was expressed with respect to the possibility of adverse environmental impacts if the option were used at scale, impacts were generally seen to be restricted to soil and air quality, localised and few in number. **Air capture and storage** also scored relatively highly against environmental criteria, albeit with a greater degree of variability. The risk of less secure and leaking geological reservoirs featured prominently in interviews, alongside environmental concerns relating to the acquisition of resources demanded over the option's lifecycle. This contrasts with more optimistic assessments elsewhere in the literature (e.g. Lackner *et al.*, 2012). On the other hand, specialist participants valued its likely regulation, monitoring and 'switch off' controllability.

Described as an 'emergency measure' by one participant (E), **stratospheric aerosol injection** performed consistently very poorly against environmental criteria. A swathe of foreseeable and transboundary impacts were raised, including stratospheric ozone depletion; effects on global circulation and regional weather patterns; shifts in the Inter-Tropical Convergence Zone (ITCZ) threatening rainfall in sub-Saharan Africa and the Indian Monsoon; as well as unforeseeable side effects. Such concerns resonate elsewhere in the literature (e.g. Rasch *et al.*, 2008). These risks were often cited from the results of climate modelling studies, which were seen to be highly uncertain and conservative themselves. Novel threats such as a 'termination problem', also outlined in Matthews & Caldeira (2007), whereby a sudden and rapid temperature rise occurs, with the magnitude and rate determined by the previously masked atmospheric CO_2 concentration following a cessation of stratospheric aerosol injection, as well as the continued impacts of ocean acidification, were also cited. Concern over the 'irreversibility' (H) of many of these environmental risks and the potential 'tipping' of Earth systems into alternate states was also raised.

> 'I'm worried about changing weather patterns and changing them irrevocably. There are certainly inelasticities in the Earth system and once you've flipped it into a new state it won't go back... Maybe there are some tipping points for sulphur in the atmosphere... It's not because I'm an environmentalist, far from it, I'm an engineer. My professional judgement is that's a bad idea' (I).

Specialist G judged the environmental side effects of the option to be unacceptable, and ruled it out on principle.

Of the discretionary geoengineering options, **space reflectors** performed most highly, scoring moderately but with a large range of variability. It was viewed that the option could be 'switched off' faster than the other solar geoengineering proposals under consideration, but that:

> 'It comes with the same problem that the other [solar geoengineering options] come with. In that it may be very efficient at reducing the amount of radiation against the Earth's surface, but what that does to stratospheric circulation, rainfall, large-scale weather patterns, isn't really clear' (E).

Cloud albedo enhancement similarly scored moderately with a large range of variability. Whilst faster to switch off than stratospheric aerosols, the size of the cloud condensation nuclei it would produce were viewed as a critical risk, echoing research that found the method could reduce cloud cover rather than enhance it (Alterskjar *et al.*, 2012). Should the particles become too large, a warming effect would replace the intended cooling effect: 'It's in the same risk category as stratospheric aerosols in the Royal Society report for a reason' (E). **Iron fertilisation** scored poorly with a large range of variability, echoing the 'very poor' safety rating attributed by the Royal Society (2009). Its potential impacts on the marine ecosystem were seen as unpredictable, but comparable with the impact of agriculture on terrestrial ecosystems, potentially bringing about a shift in species composition, toxic blooms (see also Gilbert *et al.*, 2008), monocultures, and dead zones. The environmental impacts of this proposal caused particular alarm with Specialist C, who described iron fertilisation as 'The scariest of the lot, other than doing nothing'.

Afforestation was the highest performing additional geoengineering option, scoring very highly with very little uncertainty. Biodiversity was seen as likely to suffer with the selection of tree species with greater CO_2 sequestration potential, echoing some wider issues of land-use change highlighted by the Royal Society (2001), whilst impacts associated with land-use change were seen as manageable. An **air capture set carbon price** scored highly with very little uncertainty pertaining to the impacts of construction and possible water pollution. **Closed-loop air capture** performed less well than its set carbon price counterpart, scoring moderately with very little uncertainty. This was due to the associated need for more processing stations and a more distributed operation. **Enhanced weathering** scored moderately with a moderate degree of variability. Whilst certainly not benign, it was viewed as less of a concern than iron fertilisation:

> 'The impacts should be less than iron fertilisation because with that you're deliberately manipulating an ecosystem... With enhanced weathering the manipulation would only be a side effect... which is chemical rather than biological' (C).

5.2.2.2 The environmental impacts of different mitigation options

The **voluntary low carbon living** option scored very highly against environmental criteria, with specialist participants often expressing difficulty in thinking of any adverse effects. The inadvertent use of higher carbon goods through the pursuit of low carbon goods was cited as a limitation, as was the possible environmental impacts of using alternatives to carbon. **Offshore wind energy** also performed highly, with some variability. Risks to birds and marine life were raised alongside more serious concerns regarding the large quantities of infrastructure to be manufactured, deployed, maintained and decommissioned at scale.

A **new market mechanism** performed reasonably highly against environmental criteria, but with a high degree of variability. Whilst some viewed the option as relatively benign, many others raised the problem of 'perverse incentives' in which certain activities are encouraged, in this case reducing CO_2 emissions, but inadvertently increasing environmental degradation elsewhere through the impacts of incentivised alternatives.

Of the discretionary mitigation options, a **carbon tax** performed most highly but with a high degree of variability relating to where the revenue was directed. If it were directed towards 'good' (L) renewable energy schemes it would be beneficial, whereas if directed towards other schemes such as biomass, it would be harmful to biodiversity. **Nuclear fusion energy** also scored highly but a high degree of variability relating to the risks associated with the safe containment of nuclear waste materials. **Nuclear fission energy** scored moderately but with a very large range of variability. Echoing the appraisal of nuclear fusion energy, environmental concerns were related primarily to safety and the risk of nuclear accidents, in addition to managing the legacy of radioactive waste. **Coal energy with CCS** scored moderately with a moderate range of variability. Specialist I viewed the only environmental impacts as being those associated with continued mining for coal, in particular opencast mining: 'It's a messy business'. Concurrently, other specialist participants cited the risk of (manageable) 'leaks' (H) and the storage of captured CO_2 at land or sea, with the latter risking harm to marine biodiversity.

With no obvious unintended consequences, **end-use efficiency enhancement** performed the most highly of the additional mitigation options, scoring the maximum possible score with no uncertainty. An **agricultural emissions reduction** scored moderately with a moderate degree of uncertainty. Whilst 'Slowing deforestation down can only be a good thing' (L), possible unintended impacts were highlighted in relation to the engineering of genetically modified organisms to reduce emissions or fertiliser dependency. Investment in **low carbon R&D** scored moderately with some uncertainty related the consequences of researching technologies that may fuel a 'moral hazard'. A **cultural transformation** scored moderately with a moderate degree of uncertainty. Whilst its stated aim was to reduce anthropogenic pressures on the environment, Specialist B added that 'there'll always be some'.

5.2.2.3 The environmental impacts of business as usual

Business as usual performed very poorly, with some variability related to climate sensitivity, impacts and adaptability. Specialist participants acknowledged that the environmental impacts of business as usual, and of the resulting climate changes, would be severe, with Specialists G, J and K ruling the option out on principle. On the other hand, Specialist B was more optimistic about the capacity for people to adapt to the impacts of climate change than others. A particularly interesting discourse that emerged surrounding business as usual was whether it would perform better or worse against environmental criteria than stratospheric aerosol injection. Three distinct positions emerged, with one specialist remarking that 'business as usual is never going to be a better option than geoengineering' (E); another that '...the risk is probably about the same' (I); and another that '…with stratospheric aerosols we're actually exacerbating the risks' (B). As well as reflecting uncertainty around the side effects of stratospheric aerosols, this also reflects a complexity of ethical positions relating to geoengineering as a 'lesser evil' as critiqued by Gardiner (2010).

5.2.3 Feasibility

5.2.3.1 The feasibility of different geoengineering proposals

Of the three core geoengineering options, **biochar** scored most highly against feasibility criteria, albeit modestly and with some variability. Whilst its local scale feasibility was cited, specialist participants expressed potential spatial and practical difficulties in scaling up the operation. Without large scale field trials, it was said, these uncertainties would remain, reflecting sentiments made in Lehmann (2007). **Air capture and storage** scored highly in principle, with Specialists C and H noting that they had either held or indeed bought a flask of CO_2 that had been captured from the air. However, the option scored poorly in terms of its technological maturity and the fact that it had not been proven to work at scale. This finding echoes the recent US Government Accountability Office report, which placed air capture and storage at Technology Readiness Level 3 (of a maximum of 9) (US GAO, 2011). Limits to that scalability were also cited, with reference to the availability of geological reservoirs. Specialist I proposed that this issue could be overcome through 'carbon recycling' rather than storage, through air capture with 'closed-loop utilisation'. However, this proposal would negate the option's negative emissions capabilities.

Stratospheric aerosol injection generally scored poorly against feasibility criteria, but with a considerable range of variability. As with air capture and storage, stratospheric aerosol injection was seen to be highly feasible in principle, but scored very poorly in its potential practice. This finding contrasts with the high engineering feasibility conferred in Fox & Chapman (2011). One specialist participant commented that:

> 'It's technically easy. From a technical point of view I could do it tomorrow afternoon. Just get a Boeing 737 and convert it and take a load of sulphur up there and do it' (I).

On the other hand, other specialists cited potential difficulties in achieving the desired particle size and dispersion in the stratosphere, and that these difficulties would not be understood until field trialling had begun. Another Specialist (E) drew on recent experiences with the Stratospheric Particle Injection for Climate Engineering (SPICE) project, noting that aspects of feasibility that needed to be tested 'outside the lab' would be constrained not only by technical limitations but also social issues.

Of the discretionary geoengineering options, **cloud albedo enhancement** performed moderately with some variability. With a perceived shorter development lead time than stratospheric aerosol injection owing to its field experimentation (e.g. Russell *et al.*, 2013), Specialist E argued that:

> 'You can begin to do it tomorrow if you wanted to. In fact, E-PEACE [the Eastern Pacific Emitted Aerosol Cloud Experiment] has already done it' (E).

This experimentation was, however, about understanding aerosols in the marine boundary layer rather than about cloud albedo enhancement *per se*. The option outperformed space reflectors and iron fertilisation which both performed poorly with a moderate degree of variability. Whilst the technology for implementing **space reflectors** was viewed as being advanced, its development lead time was seen as being very long. In agreement with other research (e.g. Boyd *et al.*, 2007), **iron fertilisation** was viewed as feasible in that iron could be applied to the oceans to stimulate algal growth, but was uncertain with respect to its mechanism for CO_2 sequestration:

> 'We have massive doubts about its effectiveness… we know we can make blooms, but we don't know how much is going to get sequestered' (C).

Three of the additional geoengineering options score very highly against feasibility criteria. **Afforestation** was seen most favourably in this respect, attaining the maximum possible score with no uncertainty: 'People are doing it now' (E). An **air capture set carbon price** scored very highly too, with very little uncertainty: 'To me this is, from a technical and socio-political standpoint, this is the absolute winner' (I). The option was viewed as both easier to implement than rebuilding infrastructure for which it was too expensive to mitigate CO_2 emissions, and capable of integration with existing frameworks including carbon markets and the United Nations Framework Convention on Climate Change (UNFCCC). **Closed-loop air capture** also scored highly with very little uncertainty. On the other hand, **enhanced weathering** scored moderately with a large range of uncertainty. Compared with iron fertilisation, the option was viewed as feasible in that minerals could be applied to soils or the ocean, but was uncertain as to how feasible its mechanism for CO_2 sequestration was.

5.2.3.2 The feasibility of different mitigation options

The **voluntary low carbon living** option scored relatively highly against feasibility criteria, with some variability. Specialists viewed the option as very easy to do both technically and practically on an individual basis, but alongside the caveat that considerable social and economic barriers would constrain its feasibility at scale. Specialist I denounced the option as being synonymous with business as usual, and ruled it out on principle. **Offshore wind energy** also scored relatively highly with some variability. The successes of existing and planned offshore wind energy projects were cited, but so too were potential maintenance and logistical difficulties in operating them at scale and over their lifecycles.

A **new market mechanism** scored moderately, but with high variability relating to perceived slow development time, complexity at scale and perceived problems with securing an effective carbon price. Specialist I noted that this latter issue could be addressed if the option were combined with a variant of air capture and storage which could be used to set the carbon price, as outlined in Fox (2012), based on the financial cost incurred to 'correct' the economic externality.

Of the discretionary mitigation options, **coal energy with CCS** was the highest performing option against feasibility criteria, scoring highly with some variability. Whilst 'The underlying technology is very mature' it was uncertain because 'No one's actually done it' (H). A **carbon tax** also scored highly, with moderate variability related to the complexity of its implementation. **Nuclear fission energy** scored moderately due to its advanced state, albeit with a large range of variability related to the finite nature of the resource and its difficulties in radioactive waste disposal. **Nuclear fusion energy** scored poorly, but with a high degree of variability. Whilst existing experimental trials were cited as encouraging, some pessimism was expressed over its timescale of feasibility: 'I just don't see it being feasible in the next fifty years' (L).

Of the additional mitigation options, both **end-use efficiency enhancement** and an **agricultural emissions reduction** performed with no uncertainty, scoring highly and moderately respectively with respect to the state of knowledge across the ensemble of criteria developed by Specialist L.

5.2.3.3 The feasibility of business as usual

Business as usual scored highly against feasibility criteria, much to the specialist participants' regret. Some variability was expressed, however, relating to resource limits associated with the unsustainable exploitation practices of business as usual; as well as a likely diminished feasibility under mounting social and political pressure.

5.2.4 Economics

5.2.4.1 The economics of different geoengineering proposals

Of the three core geoengineering options, the economics of **stratospheric aerosol injection** was the most variable. Specialist participants expressed this uncertainty as differences in what might be included in the option's base cost. If the base cost was considered purely in terms of the resources required to operate stratospheric aerosol injection, it scored very highly. One specialist commented:

> 'It's terrifyingly good value for money... just purely on a technological delivery basis it's probably on the order of around a billion dollars. So if it gets to the point where Richard Branson or Bill Gates-. If one of those could do it themselves, it's terrifyingly cheap' (E).

However, if the base cost was to include the potential economic costs incurred by adverse side effects caused through the use of stratospheric aerosols, it scored poorly. Specialists cited the potential need for compensating regions that suffered adverse impacts, as well as the on-going costs associated with a reliance on stratospheric aerosol injection in order to avoid the 'termination problem' (Matthews & Caldeira, 2007). Other cost variables included the different costs of alternative delivery mechanisms and the standards of safety enforced on condition of the option's use. These findings would suggest that the economics of stratospheric aerosol injection are not 'incredible' after all, confirming conjecture by Robock (2008) and conflicting with other consistently favourable claims (e.g. Barrett, 2008; Bickel & Lane, 2000; Keith & Dowlatabadi, 1992; Keith, 2000; Levi, 2008).

Biochar performed moderately against economic criteria, but with a degree of variability. Its economics were seen to depend greatly on the scale at which it would be applied, with larger scale operations seen as increasingly expensive, resonating with other, more specific concerns in the literature regarding feedstock transportation (Roberts *et al.*, 2010). Specialist H noted viable economic markets open to biochar, but cited difficulties in securing sales and investment being experienced by existing companies. **Air capture and storage** performed poorly against economic criteria, with some variability associated with potential technological breakthroughs, different technology designs and wildly contrasting estimates of cost per tonne of CO_2 captured communicated by air capture proponents and their critics. The overall poor performance contrasts sharply with the possible 'appraisal optimism' (Flyvjberg *et al.*, 2003) of proponents (e.g. Keith *et al.*, 2005). On the other hand, the option was seen to lend itself to private commercial pursuits, but given the quantities of air that needed to be processed, together with a legacy of infrastructure, maintenance and storage costs, it was viewed as unlikely to ever be cheap.

Of the discretionary geoengineering options, **cloud albedo enhancement** performed the most highly, scoring moderately overall but with a very large range of variability. Such uncertain optimism reflects preliminary cost estimates in the literature (e.g. Salter *et al.*, 2008). Specialist E compared the deployment costs with those of stratospheric aerosol injection, again describing them as globally 'terrifyingly cheap'. Variability originated with contrasting estimates of the cost of developing and constructing the technology. **Iron fertilisation** scored poorly against economic criteria, with a large range of variability. Whilst viewed as relatively cheap to simply deploy the iron to the oceans, reaffirming the assessment made by the Royal Society (2009), 'You're not going to have much effect, so on a value for money basis it may not be great' (C). Described as 'bonkers expensive' (E), **space reflectors** scored very poorly with little variability, echoing the findings of the Royal Society (2009) in spite of more optimistic assessments (e.g. Keith, 2000), owing to the perceived costs in manufacturing the reflectors and transporting them into orbit.

Of the additional geoengineering options, three performed particularly highly against economic criteria. An **air capture set carbon price** scored very highly with little uncertainty. Described by Specialist I as employing 'irrefutable logic' in its attribution of the cost of pollution caused by CO_2 in the atmosphere, echoing sentiments made by Fox (2012), they further argued that:

‘I think this could be brilliant for the economy because it would really drive innovation and it would force markets to work properly’ (I).

Closed-loop air capture scored highly with little uncertainty. Comparing the option directly with an air capture set carbon price, Specialist I argued that here it would incur costs through chemical processes in its ‘utilisation’ aspect: ‘With [the former] you’re using air capture as a market driver, here it’s a cost... a commodity’. Described as ‘incredibly cheap’ (E), **afforestation** performed highly with some uncertainty. **Enhanced weathering** scored poorly with some uncertainty around the costs of extracting and transporting the vast quantities of minerals needed, contrasting sharply with more optimistic assessments elsewhere in the literature (e.g. Schiling & Krijgsman, 2006).

5.2.4.2 The economics of different mitigation options

Of the three core mitigation options, the **voluntary low carbon living** option scored most highly. Most specialist participants viewed the option favourably as it would not be adopted unless it was affordable. Higher level costs, however, such as running a social marketing campaign were viewed as potentially greater, given their need to compete with the greater marketing budgets of business as usual. A **new market mechanism** also scored highly, but with some variability. It was noted that its very premise was to be economically efficient, but that existing market mechanisms had suffered from a ‘chronically undervalued’ (E) carbon price. On the other hand, it was seen to be beneficial for stimulating innovation, and by extension the economy, through new markets and businesses.

Offshore wind energy scored moderately against economic criteria, with some variability surrounding the policy framework in which it would operate. Considerable costs associated with the legislative planning, installation, grid connection, maintenance and decommissioning of offshore wind turbines were cited as reasons for concern alongside high electricity costs passed on to consumers. Despite these reservations, specialist participants noted that achieving economies of scale, future investment and technological advancements would likely reduce these costs.

Nuclear fission energy performed most the most highly against economic criteria of the discretionary mitigation options, scoring highly but with a moderate degree of variability relating to the costs associated with radioactive waste disposal. A **carbon tax** also scored highly with respect to its implementation, but with a moderate degree of variability surrounding market stability risks.

Coal energy with CCS scored moderately, also with a moderate range of variability. The cheapness and availability of coal were cited as strengths, whilst penalties for its degradation of the environment were cited as weaknesses. **Nuclear fusion energy** scored poorly for its 'infinitely expensive' (L) development and public investment, but comprised a high degree of variability owing to uncertainties about the length of its development time and the final cost of its energy.

Of the additional mitigation options, a **cultural transformation** scored the maximum possible score with no uncertainty. Whilst Specialist B noted that the economics of this option largely depended upon how it was implemented, whether through governments or social movements, it was 'Not a matter of public investment, it's a matter of cultural values' (B). A **national policy framework** scored very highly with little uncertainty, owing to its capacity to 'save money [and] generate jobs' (F). **End-use efficiency enhancement** scored highly with a moderate range of uncertainty: 'You'd only do it if it was economically efficient' (L). Investment in low carbon R&D scored moderately with little uncertainty, involving a reorientation and supplementation of research budgets. An **agricultural emissions reduction** scored poorly with some variability. Whilst reductions in deforestation were viewed as being 'as cheap as Hell' (L), reducing agricultural emissions was seen as more difficult.

5.2.4.3 The economics of business as usual

Business as usual performed poorly against economic criteria, with specialist participants noting its beneficial generation of economic activity, but extensive unintended costs. Specialist F deemed the costs that would be incurred to the world by climate change though pursuing business as usual 'would be off the scale', and ruled the option out on principle.

5.2.5 Politics

The scores of option performance against political criteria bore some relationship with issues of society. Specialist participants sometimes drew upon social issues that would have political implications.

5.2.5.1 The politics of different geoengineering proposals

Of the three core geoengineering options, **biochar** performed the most highly against political criteria. Specialist participants cited its politically attractive 'win-win sales talk' (C) and the fact that it is already practiced, albeit on a small scale. However, some variability was expressed when considering the option's performance at larger scales of deployment, where more people would be affected by its use. **Air capture and storage** also performed highly against political criteria. Whilst specialists cited no need for multilateral agreements for its use, reaffirming its territorial operation in Humphreys (2011), and its compatibility with private commercial uptake, politically sensitive risk issues were noted surrounding the siting and safety of carbon storage facilities.

Stratospheric aerosol injection scored very poorly against political criteria. It was seen as an incredibly difficult political issue, even under a best-case scenario where multilateral negotiations would be pursued. Specialist participants expressed significant doubts about its viability, given the diverse cultural and vested interests that have confounded existing attempts to secure a global agreement to mitigate. The fact that no legal framework or governance structures are in place gave rise to concerns over the risk of unilateral deployment, reflecting those aired by the Solar Radiation Management Governance Initiative (SRMGI, 2011). One specialist commented that:

> 'There is no legal framework, there's nothing to prevent it and nothing to commit it. In terms of international law, it's a black hole' (C).

The global risks that might arise from such an endeavour raised issues of geopolitical tensions and of the need for compensation mechanisms to recompense regions that suffered adverse impacts. Specialist K considered stratospheric aerosols to be politically unacceptable, and ruled the option out on principle without sufficient governance to control it.

Of the two discretionary geoengineering options subject to appraisal against political criteria, **cloud albedo enhancement** scored moderately with some uncertainty surrounding its acceptability. **Iron fertilisation** scored poorly against political, with a moderate range of variability. Its legal infringement of international laws such as the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972) were seen as problematic, but not beyond re-negotiation.

> 'Politically it's a problem because you're interfering with natural ecosystems that don't respect national boundaries' (C).

The one additional geoengineering option subject to appraisal against political criteria, **enhanced weathering**, scored poorly with some uncertainty. Specialist C argued that it should be treated in a similar manner as iron fertilisation with respect to its potential violation of international laws.

5.2.5.2 The politics of different mitigation options

Offshore wind energy scored the most highly of the three core mitigation options. It was cited as being politically more acceptable than its onshore counterpart, notwithstanding aesthetic objections from coastal communities. Specialist participants viewed these objections as being increasingly likely with scale. The **voluntary low carbon living** option performed moderately against political criteria, with specialists citing its voluntary nature as unlikely to generate political tensions. Concurrently, the option was criticised for lacking political leadership and drive, as well as needed regulation.

A **new market mechanism** scored moderately against political criteria, but with a high degree of variability. Whilst the option was viewed favourably in that it would not affect citizens in any visible way, difficulties surrounding the willingness of different nations to participate were seen as unlikely to lessen. Specialist F also raised the contested issue of historical emissions and the burden of responsibility, and the potential for the option to be construed as a neo-colonial constraint to development.

Of the discretionary mitigation options, **nuclear fission energy** bore the greatest uncertainty, stretching from the minimum to the maximum score. It was seen to vary substantially from nation to nation, with some, such as France, enthusiastic, but others, such as Germany, either phasing out their nuclear fission energy or unenthusiastic about taking it up. Similarly, the political acceptability of a **carbon tax** was viewed as variable between nations, and dependent upon the mode of its operation, scoring moderately overall, with moderate variability. **Nuclear fusion energy** scored highly with some uncertainty relating to 'technical breakthroughs' (B) necessary for securing funding.

Of the two additional mitigation options subject to appraisal against political criteria, a **national policy framework** performed moderately with some uncertainty surrounding a perceived lack of political will at both the national and international level. To the regret of Specialist B, a **cultural transformation** scored poorly with some uncertainty, being seen as unlikely to happen despite 'one or two little steps being tried in France and Scandinavia and Britain' (B).

5.2.5.3 The politics of business as usual

Business as usual scored highly against political criteria. Much as with its performance against feasibility criteria, it was with specialist participants' regret that change was politically undesirable.

5.2.6 Society

5.2.6.1 The social implications of different geoengineering proposals

Biochar scored reasonably highly against social criteria, with some variability. Its well established use, potential improvements to agricultural yields and publically perceived 'naturalness' were all viewed as positive aspects of biochar. These findings lend support to the positive public perceptions recorded in the NERC (2010) Experiment Earth public dialogue. However, specialist participants often cited the potential for land-use conflicts with biochar practiced on larger scales, and a number of vocal oppositional non-governmental organisations. **Air capture and storage** scored moderately, with some variability associated with its safety and its aesthetic value. Public fears of sudden CO_2 release were expressed, citing the 1986 Lake Nyos outgassing as an analogy (BBC, 1986). Specialists often used onshore wind turbines as an analogy for the aesthetics of air capture and storage, noting the risk of potential 'NIMBYism' (Gipe, 1995).

Stratospheric aerosol injection scored very poorly against social criteria, with variability relating to its very premise, distribution of effects and deployment. In its best case specialist participants said the option mirrored a natural system, that of a volcanic eruption. Specialist E remarked that:

> 'Stratospheric aerosol injection rightly scares the [expletive] out of everybody, which actually I don't think is a bad thing at all' (E).

Specialist L commented that the very idea was likely to be met with public hostility, whilst Specialist E cited a 'reluctant acceptance'. This latter view finds resonance in recent public engagement research (Macnaghten & Szerszynski, 2013) and more specifically, with the SPICE project (Parkhill & Pidgeon, 2011; Pidgeon *et al.*, 2013). The social inequities risked by an uneven distribution of the option's effects were raised often by specialists, citing secondary impacts of environmental risks. Strong opposition from non-governmental organisations was also cited, and was indeed reflected in the scores given by civil society Specialist G, but Specialist K added that technological robustness and satisfactory governance could help mitigate concerns. Specialists A and G judged the social acceptability and socioeconomic impacts of the option to be unacceptable, and ruled the option out on principle.

Of the discretionary geoengineering options, **cloud albedo enhancement** performed most highly, scoring moderately overall but with a large range of variability. Directly contrasted with stratospheric aerosol injection by three of the four specialist participants who selected the option for appraisal, it was viewed as potentially more acceptable in appearance. The following comment was typical:

> 'I suspect [the public] feel much better about cloud albedo enhancement than they do about stratospheric aerosol injection, because scary balloons with acid are one thing, but little fluffy clouds is something else. Despite the fact that they're not that dissimilar in terms of risk' (E).

In brief moments of respite, **space reflectors** became the subject of humorous comment with respect to social criteria. The following comment was typical:

> 'I think some people love the idea of space mirrors actually, a couple of international villains out there would love the idea of having a giant mirror in space. I suppose most people think it's completely ridiculous and rate it pretty low' (H).

On a more serious note, its controllability noted as being higher than other solar geoengineering proposals and hence likely to be more socially acceptable. This acceptability was not found in the Experiment Earth? public dialogue, where it was viewed as unrealistic, infeasible, expensive and risky by many participants (NERC, 2010). **Iron fertilisation** also scored poorly with a moderate range of variability. The prospect of dumping material in the ocean was seen as likely to incur negative public views based on its questionable efficacy and likely impact on marine ecosystems. Indeed, this was the finding of in the Experiment Earth? public dialogue, where the proposal was viewed as unpredictable and risky (NERC, 2010).

The one additional geoengineering option subject to appraisal against social criteria, **afforestation**, scored very highly with little uncertainty, resonating with its high performance in the Experiment Earth? public dialogue (NERC, 2010). Perceived as universally acceptable by Specialist E, it was viewed as both safe and logical.

5.2.6.2 The social implications of different mitigation options

The **voluntary low carbon living** option performed highly against social criteria, as it was seen to be unforced and therefore acceptable. Specialist A remarked that if you could 'sell the sizzle' (cf. Futerra, 1996), or successfully encourage low carbon behaviours, the approach would perform very well indeed. However, specialist participants often noted the option's inherent conflict with people's lifestyles and their deep rooted practices, which would discourage its adoption. Specialist K noted that many nations are already living low carbon lifestyles through their being less developed, so such a proposal would be unproblematic. **Offshore wind energy** scored highly against social criteria, but with some variability. As with the political criteria, it was cited as being more socially acceptable than its onshore counterpart, notwithstanding aesthetic objections from coastal communities. On the other hand, its cost of electricity to the consumer was cited as being expensive in the face of cheaper, but higher carbon, alternatives.

A **new market mechanism** scored moderately against social criteria, with some variability. As with the political criteria, it was viewed favourably in that it would not affect citizens in any visible way, but this was likely to differ greatly between nations. Specialist G also raised concerns about the mechanism's potential for creating unfairly distributed socioeconomic impacts, citing existing Clean Development Mechanism (CDM) projects to develop biofuels. The extent of these risks was judged by Specialist G to be unacceptable, and they ruled the option out on principle.

Of the discretionary geoengineering options, a **carbon tax** performed the most highly, scoring moderately overall but with a large range of variability owing to rises in energy prices. **Coal energy with CCS** scored moderately, and with a moderate range of variability. Proximity to the site of this option was seen as the main concern, with people's perceptions seen as likely to compare with those for onshore wind energy and potentially, air capture and storage. **Nuclear fission energy** scored moderately but with a large range of variability concerning the risk of accidents and the safe disposal of radioactive waste. **Nuclear fusion energy** scored poorly and with a large range of variability. Whilst the idea in principle was viewed favourably by Specialist H, Specialist L argued that it would be regarded as similar to nuclear fission and its associated risks, despite being 'totally different'.

Of the additional mitigation options, **end-use efficiency enhancement** score the most highly, attaining the maximum possible score with no uncertainty: 'People won't do it unless they accept it, it's a voluntary thing' (L). A **national policy framework** scored moderately, and with a moderate range of uncertainty related the possible policies that might result:

'Would people object? They would if it hit them in the pocket... Presented as green jobs, presented as Britain leading a new green global economy, and jobs for everybody and this is how we're going to make our wealth in the 21st Century, then you could sell it to people' (F).

An **agricultural emissions reduction** scored poorly, with a moderate range of uncertainty relating to perceptions of risking food security and increasing food prices.

5.2.6.3 The social implications of business as usual

Business as usual scored moderately against social criteria, but with some variability. The poverty alleviation brought about through business as usual was seen as socially beneficial, and public perceptions of the resultant climate change itself were viewed as conservative and therefore of limited social concern. However, specialist participants argued that strong opposition from non-governmental organisations would impact, as would the increasingly apparent impacts of climate change. Indeed, the socioeconomic impacts over time were viewed by Specialist G to be unacceptable, who ruled the option out.

5.2.7 Ethics

5.2.7.1 The ethics of different geoengineering proposals

Of the three core geoengineering options **biochar** performed most highly in relation to ethical criteria, scoring moderately with some variability. Its localised nature was seen by specialist participants to be less troubling, even beneficial, compared to those options with global implications. However, biochar was said to potentially pose similar social and environmental risks to biofuels if used at scale, with the imposition of risks and benefits on certain people, and the large-scale reorientation of agricultural production. **Air capture and storage** performed poorly, with some variability. Ethical concerns were largely related to the option's storage aspect, citing safety aspects of the CO_2 storage. Whilst a 'waste product' was involved, Specialist D remarked, the option would be beset by similar problems as those experience by nuclear fission energy, with its radioactive waste. This lends support to the additional option of air capture and closed-loop utilisation separately proposed by Specialist I, which however would not remove CO_2 from the atmosphere.

Stratospheric aerosol injection scored very poorly against ethical criteria, with very little variability. It was widely held to pose difficult and unpredictable ethical disputes. The issue of consent was deemed to be a core ethical consideration, reflecting concerns noted by Corner & Pidgeon (2010), with Specialist D remarking:

> 'I don't envisage a set of circumstances in which you could ever get something that looked like consent, either informed and given, or assumed, in anything like a satisfying way' (D).

The same specialist also stated that the ethics of possible unilateral deployment '…are tantamount to war'. Specialists A and G considered concerns over the option's ownership, control and distributed impacts to be unacceptable, and they ruled the option out altogether.

The one additional geoengineering option subject to appraisal against ethical criteria, **iron fertilisation**, performed very poorly with little uncertainty. The principle concern related the possibility of its ownership and control by private interests: 'There can't be any private interests in dumping stuff in the oceans' (G).

5.2.7.2 The ethics of different mitigation options

Of the three core mitigation options, the **voluntary low carbon living** option scored most highly, with some variability relating to its ability to reduce social inequalities. Specialist A noted that the option could be socially progressive depending upon the specific approaches adopted, citing the potential of personal carbon allowances. On the other hand, Specialist B argued the option could prove socially regressive where policies such as the UK's Feed in Tariff are publically funded via subsidies, but its uptake is restricted to only those with capital to afford the photovoltaic cells, essentially transferring money from the lower classes to the middle classes.

Offshore wind energy performed moderately with respect to its creation of industry and jobs, but some variability was expressed around its uneven imposition upon people. The option's high energy prices were viewed to be socially regressive. A **new market mechanism** performed poorly against ethical criteria. It was argued to raise a significant set of ethical questions around the new sets of 'winners' and 'losers' it would create.

Of the two discretionary mitigation options subject to appraisal against ethical criteria, a **carbon tax** performed moderately, albeit with a large range of variability. Much of this variability related to the ways in which such a tax might be implemented, resulting in either socially progressive or regressive policies. Its centralised, but governmental, ownership and control was also viewed more positively by civil society participant Specialist G than for options subject to private control. **Nuclear fusion energy** performed poorly, with some uncertainty relating to pessimism about the option's ultimate energy prices and their impact (or non impact) on improving access to energy.

Of the two additional mitigation options subject to appraisal against ethical criteria, investment in **low carbon R&D** performed most highly, scoring highly with some uncertainty related to the investment in potential 'false hopes' research rather than tackling 'people's genuine needs' (D), and the possibility of diminishing responsibility and incurring a moral hazard. A **cultural transformation** scored moderately as 'a value system that is inherently less hierarchical' (B) but with some uncertainty relating to the persistence of existing inherent inequalities.

5.2.7.3 The ethics of business as usual

Business as usual performed poorly against ethical criteria, albeit with some variability. Specialist D noted that the ethics of 'carrying on' were unproblematic, as were those of its 'unintentional' impacts. Specialist B stated that whilst business as usual was likely to be reducing global inequalities in absolute terms, there were considerable variations within and between countries. Specialist G considered the prioritised interests of business over other considerations, including intergenerational equity, as unacceptable, and ruled the option out on principle.

5.2.8 Co-benefits

This 'other' criterion was appraised in isolation by only Specialist B, but some themes of co-benefits were seen to run throughout the other specialist participants' interviews under different criteria, despite not having been explicitly addressed.

5.2.8.1 The co-benefits of different geoengineering proposals

Of the three core geoengineering options, **biochar** performed most highly against the co-benefit criterion, scoring moderately through its co-benefits to agriculture, namely: improved soil conditioning; increased water retention and related lowered irrigation demands; and increased productivity and yields. **Air capture and storage** scored very poorly, with no co-benefits identified. In agreement with other research (Hulme, 2012), **stratospheric aerosol injection** scored very badly, with Specialist B remarking at its likely 'co-problems' if anything, including a possible contribution to ozone depletion.

5.2.8.2 The co-benefits of different mitigation options

Voluntary low carbon living was seen to perform moderately against the co-benefit criterion, with personal benefits cited. **Offshore wind energy** scored moderately too, with improved energy security and health co-benefits associated with air quality improvements following a departure from fossil fuel energy sources. A **new market mechanism** was viewed as spouting similar potential health benefits, but scored poorly with little else to offer.

Of the two discretionary mitigation options subject to appraisal against the co-benefit criterion, both **nuclear fusion energy** and a **carbon tax** performed poorly, with the latter markedly more so. Both options were stated to improve air quality and by extension public health by removing particulates from the atmosphere that would otherwise be released by fossil fuel energy sources, but nuclear fusion energy was believed to achieve this in a more encompassing way.

The one additional mitigation option subject to appraisal against the co-benefit criteria, a **cultural transformation**, scored very highly with little uncertainty. It was understood to offer improvements to quality of life, social inclusion, community strength, and spiritual values, thereby representing a more holistic option.

5.2.8.3 The co-benefits of business as usual

Business as usual scored highly against the co-benefit criterion, with clear social benefits associated with economic growth and poverty reduction.

5.3 Criteria Weighting and Option Ranking

With the exception of Specialist B, who preferred to weight their criteria prior to option scoring, specialist participants were invited to assign weightings to their criteria to indicate their relative importance following option scoring. These weightings are considered in Section 5.3.1 below. Subsequent to the assignment of weightings, specialists were invited to review the outputs from their appraisals, for which each participant expressed their satisfaction after some made minor adjustments to better reflect their perspectives. These outputs rankings are considered in Section 5.3.2 below.

5.3.1 Criteria weighting

The eight criteria groups are ranked according to their mean weighting for each specialist sector in Table 5.3. Whilst the mean weightings for each criteria group were similar (within 8.5% of one another), there was considerable variation between the specialist sectors and between individual specialist participants. Two specialists engaged with the weighting phase rather differently from the rest, assigning roughly equivalent values (C) or precisely equal values (K) to all of their criteria, citing hesitations at prioritising criteria under uncertainty. Academic specialists were the only sector to develop criteria that covered all eight of the criteria groups, giving weighted attention to technical, applied and social issues alike. Industry specialists, on the other hand, developed criteria that covered the least criteria groups (4) and were primarily concerned with technical issues and foremost with feasibility. Government specialists were also concerned with technical issues, albeit as part of a greater diversity of criteria. Conversely, civil society specialists gave greater weightings to social issues than did the other sectors.

Table 5.3. Criteria group weightings by specialist sector and weighted order.

Criteria group	Academic	Civil society	Industry	Government

Efficacy	3	4	-	1
Environmental	**2**	(2)	4	3
Economic	7	(1)	2	2
Social	5	**3**	(3)	6
Feasibility	8	-	1	5
=Ethical	4	(6)	-	-
=Political	6	(5)	-	(4)
Co-benefits	(1)	-	-	-

Criteria are in descending order by mean weight. Orders displayed in brackets were only used by one participant, and those displayed in bold are the highest ranking criteria notwithstanding those that were only used by one participant.

Efficacy criteria were weighted most highly overall with 7 out of the 10 participants who adopted them giving them their highest or joint highest weighting. Indeed, one specialist participant described the criteria group as 'the ultimate measure' (L). Environmental criteria were the second highest weighted group with 6 out of the 10 specialists who adopted them giving them either their highest or second highest weighting. Viewed as the criteria group that would drive decision making, economic criteria ranked highly overall, but were often given weightings at either extreme, with 2 out of the 10 specialists who adopted them giving them their highest or joint highest weighting, and 4 giving them their lowest or joint lowest weighting. Social criteria were similarly given weightings at either extreme, with 2 out of the 8 participants who adopted them giving them their highest or joint highest weighting, and 2 giving them their lowest or joint lowest weighting. Feasibility criteria were generally weighted as less important than other criteria, with the exception of Specialist I, who gave it a particularly high relative weighting (43%). Ethical and political criteria were weighted equally overall, with the former given the highest weightings by 2 out of the 4 specialists who adopted them, and the latter generally given lower weightings as a reflection of its manifest interrelations with other criteria. Developed by Specialist B only, the co-benefits criterion was given the highest weighting by that participant.

5.3.2 Option ranking

Figure 5.1 shows the final overall rankings of each specialist participant's appraisal of the seven core options. A number of key findings can be identified, the most obvious being that participant's different perspectives have amounted to different option rankings. Despite these differences, the ranks of geoengineering options are most often lower than those of the mitigation options. There are a few exceptions to this pattern, with the opposite being true for participant I.

Important nuances also emerge between the individual options. Of the core geoengineering options, at their best biochar and air capture and storage are often seen to outperform stratospheric aerosol injection, drawing a distinction between carbon and solar geoengineering options. Of the core mitigation options, at their best voluntary low carbon living and offshore wind energy are often seen to outperform a new market mechanism. Business as usual is almost consistently the worst performing option. Interestingly, its performance is not unlike that of stratospheric aerosol injection, reflecting debates recorded in the interviews about their similarities.

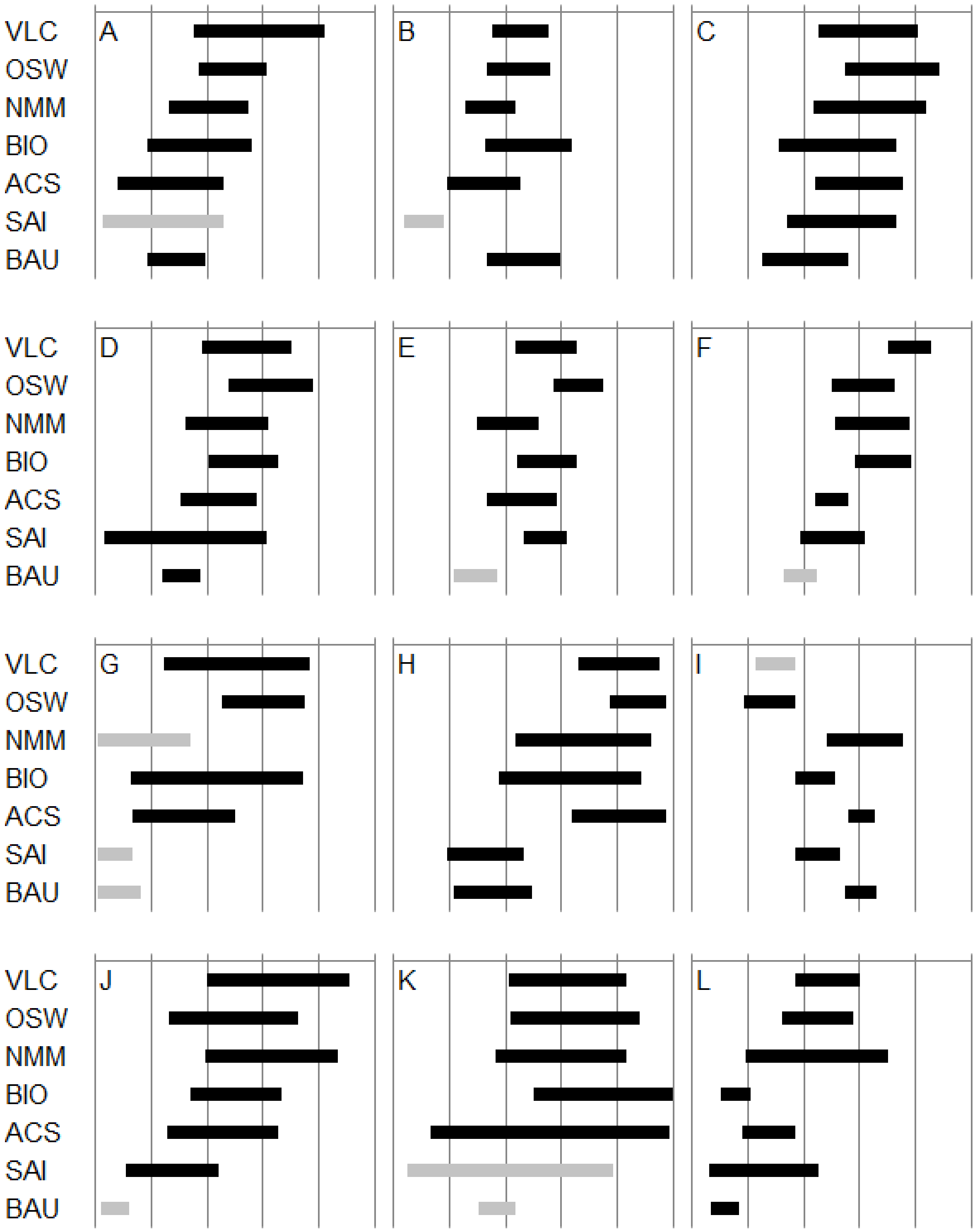


Figure 5.1. Final rankings of core options assigned by participants A - L. Acronyms: voluntary low carbon living (VLC); offshore wind energy (OSW); new market mechanism (NMM); biochar (BIO); air capture and storage (ACS); stratospheric aerosol injection (SAI); business as usual (BAU). Participants: A (Environmental social scientist); B (Interdisciplinary climate scientist); C (Earth system scientist); D (Science and technology social scientist); E (Volcanologist); F (International conservation charity manager); G (International technology action group manager); H (International commercial competition manager); I (National engineering institution manager); J (National government civil servant); K (Local government public sector officer); L (National

government scientific advisor).Performances increase on an arbitrary subjective scale to the right. Bar length represents uncertainty between the mean optimistic and pessimistic performance scores across each participant's criteria. Greyed performance ranges indicate options ruled out against at least one principle.

The uncertainties represented by the ranges between optimistic and pessimistic scores are an important feature of the rankings. Indeed, it can often be seen that better performing options are outperformed under their pessimistic scores by poorer performing options under their optimistic scores. These uncertainty ranges echo the findings of earlier MCM research by Stirling and Mayer (2001), where GM crop options were appraised against non-GM alternatives. Levels of uncertainty varied widely across all options and participants, with some participants expressing more uncertainty with geoengineering options and some more with mitigation options, despite the relative maturity of those latter options. Uncertainty around business as usual was consistently relatively low, but its different rankings reflect different participant's perspectives as to its relative risks and benefits and of the adaptability of society. Participants representing government (J, K, L) could tentatively be described as having expressed greater uncertainty than the other sectors, contrasting particularly with participant I (industry).

Figure 5.1 also shows that four core options were ruled out against at least one principle by at least one participant. In fact, voluntary low carbon living and a new market mechanism were ruled out by 1 participant each; stratospheric aerosol injection was ruled out by 4 participants; and business as usual was ruled out by 5 participants. Table 5.4 details which options were ruled out, by how many participants, against which principles. Participants who did not rule any options declared that all options needed to be explored, with participant L remarking 'We can't afford to rule any of them out'.

Table 5.4. Options ruled out by specialist participants against which principles.

Option	Principles ruled out against
C1 Voluntary low carbon living (ruled out by 1 specialist: I)	Technical feasibility
C3 New market mechanism (ruled out by 1 specialist: G)	Greenhouse gas reduction; environmental side effects; transboundary impacts; socioeconomic impacts; ownership and control
C6 Stratospheric aerosol injection (ruled out by 4 specialists: A, B, G, K)	Global temperature reduction; greenhouse gas reduction (2); environmental side effects; transboundary impacts; social acceptability; socioeconomic impacts; governance; political acceptability; distributive justice; ownership and control (2); co-benefits
C7 Business as usual (ruled out by 5 specialists: E, F, G, J, K)	Climate change impacts reduction; climatic response time; global temperature reduction; greenhouse gas reduction (2); environmental impacts; environmental side effects; transboundary impacts; cost; human impacts; socioeconomic impacts; intergenerational equity; ownership and control
D5 Iron fertilisation (ruled out by 1 specialist: G)	Greenhouse gas reduction; environmental side effects; transboundary impacts; socioeconomic impacts; ownership and control
D7 Space reflectors (ruled out by 1 specialist: E)	Cost

(2) Indicates a principle that was invoked by two separate participants in relation to the corresponding option.

Figure 5.2 shows the aggregated final overall rankings of all participants' appraisals of core, discretionary and additional options. Whilst such aggregated rankings should always be interpreted with caution, the figure includes error bars to represent the extreme optimistic and pessimistic final overall scores of individual participants, to ensure that the full range of uncertainty is represented. Indeed, panel (a) shows the uncertainty to stretch almost the full length of the performance scale for many of the core options. The aggregated scores reaffirm the findings of the individual final overall appraisals discussed in this section above and shall not be repeated here.

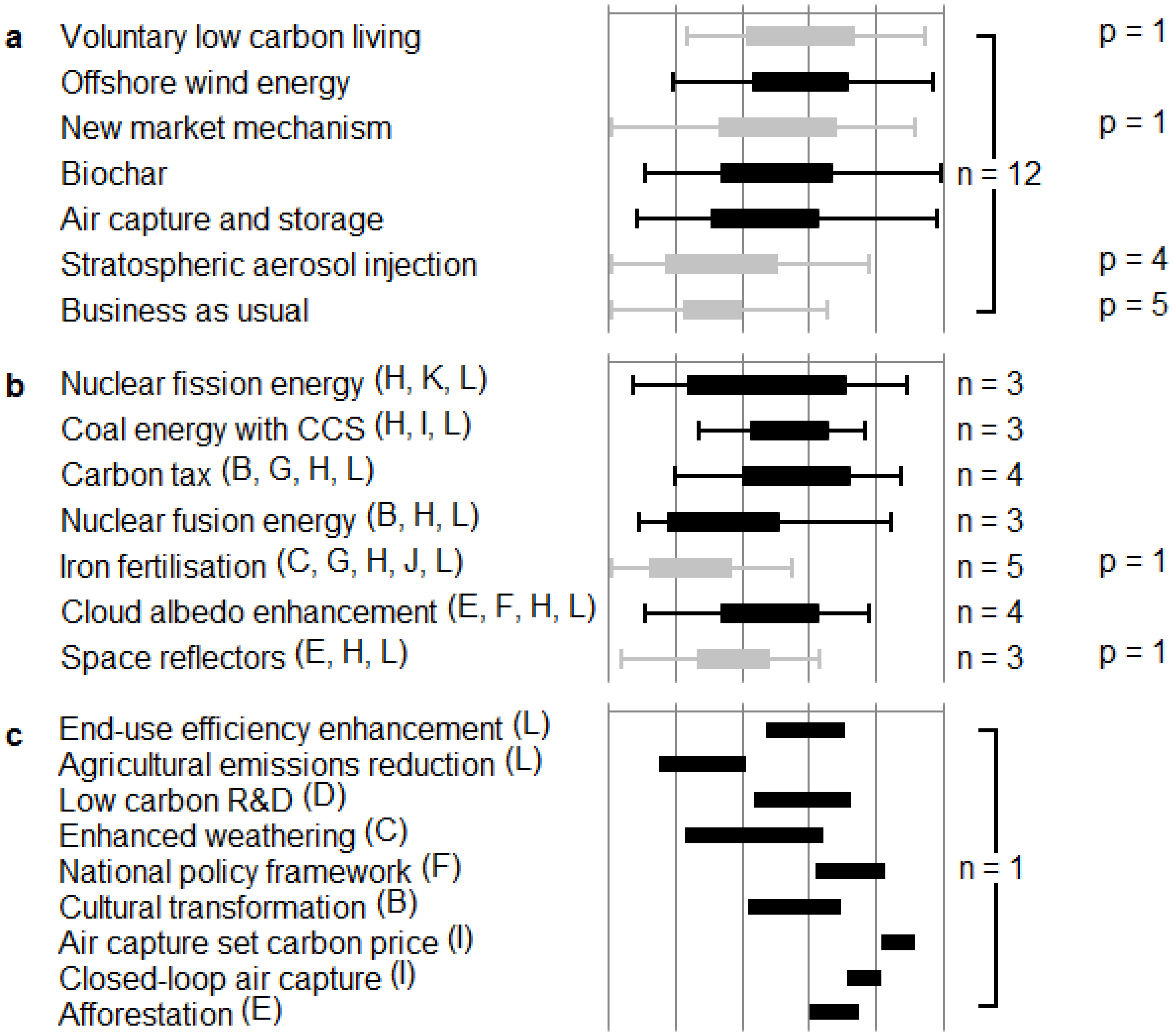


Figure 5.2. Aggregate final rankings of core options appraised by all twelve participants (panel a), discretionary options appraised by some participants (panel b, participant codes indicated beside corresponding options) and additional options appraised by individual participants (panel c, participant codes indicated beside corresponding options). Acronyms: carbon capture and storage (CCS); research and development (R&D). Frequency of participants appraising (n) corresponding options and ruling them out on principle (p) indicated to the right of the graphic. Performances increase on an arbitrary subjective scale to the right. Bar length represents uncertainty between the grand mean of optimistic and pessimistic performance scores. Range 'error' bars represent rank extrema: the maximum optimistic and minimum pessimistic scores. Greyed performance ranges indicate options ruled out against at least one principle by at least one participant. Note that options ranks on panels b and c are not on the same scale as panel a, nor are they on the same scale as one another due to different participants and participant frequencies. The relative positions of these ranking intervals are therefore much less robust than for the core options in panel a, and should be interpreted with caution.

Of the discretionary options (Figure 5.2b), mitigation options can again be seen to outperform their geoengineering counterparts. Of the discretionary geoengineering options, at its most optimistic cloud albedo enhancement was seen to outperform space reflectors and iron fertilisation.

Iron fertilisation was ruled out on principle by participant G for its questionable efficacy, risk of unintended environmental impacts, socioeconomic impacts, transboundary effects and privatised control. Space reflectors were ruled out on principle by participant E for their prohibitive financial cost. Of the discretionary mitigation options, at its most optimistic a carbon tax outperformed coal energy with carbon capture and storage and nuclear fission energy. Nuclear fission energy bore the most uncertainty, reflecting debates raised across the criteria. Nuclear fusion energy performed least well at its most optimistic, reflecting participants' pessimism over its development time or simply its viability.

Additional options (Figure 5.2c) were appraised solely by the individual participants that proposed them, often having been introduced as their favoured options. Indeed, five of these went on to outperform all other options being appraised by their proponent. These were cultural transformation (B); afforestation (E); an air capture set carbon price and closed-loop air capture (I); and end-use efficiency enhancement (L).

Conclusions

This chapter has analysed and discussed the results of the specialist strand of the DM process, and has begun to address the limitations that have beset other appraisals of geoengineering by opening up appraisal inputs and outputs to a wider diversity of framings. These framings span the options to be appraised under a broader problem definition, the criteria with which to evaluate them, criteria weightings to indicate their relative importance; and of course the diverse specialist perspectives themselves, from across academic, civil society, industry and government who have engaged in the appraisal. A range of 'additional' options were defined by specialist participants, spanning alternative carbon geoengineering proposals, mitigation options and broader cultural transformation. A diverse range and depth of eight criteria groups with which to evaluate those options also emerged, with issues spanning the natural, applied and social sciences: efficacy, environment, feasibility, economics, politics, society, ethics and co-benefits. Those more technical of the criteria were ranked most highly in their weightings, but important differences existed between different perspectives and participants.

From these diverse framings that sought to open up the appraisal of geoengineering, a radically different view of option performance has emerged compared with those of current assessments. Geoengineering proposals have performed most often lower than their mitigation counterparts. In particular, where stratospheric aerosol injection has previously outperformed other geoengineering proposal and emerged as an ostensibly effective, feasible and cheap proposal, here has performed very poorly. Its low performance ranking is not only a result of opening up appraisal criteria to a wider range, including issues of politics, society, ethics and co-benefits, but also a result of opening up appraisal criteria to a greater depth. Instead of simply being assessed against narrow, single criteria of efficacy (e.g. global temperature reduction), feasibility (e.g. delivery mechanism) or economics (e.g. cost-benefit ratio), here several different but equally valid measures of efficacy (e.g. greenhouse gas reduction, climate change impacts reduction, duration of effect), feasibility (e.g. state of knowledge, development time, resource availability) and economics (e.g. broader cost base, public investment, commercial viability) have shown that stratospheric aerosol injection, and indeed other options under consideration, do not demonstrate a robust performance across the ensemble. As would be expected, these findings and the performance of all options are subject to varying degrees of uncertainty, something that is actively explored and transparently presented by the MCM approach.

Reflexive appraisals such as the MCM approach developed in this chapter form an essential part of ambitions to realise wider frameworks of responsible innovation for geoengineering that encourage anticipatory, reflexive, inclusive and responsive forms of governing in the face of radical uncertainties and indeterminacies, competing visions and social concerns (Owen *et al.*, 2013; Stilgoe *et al.*, 2013; Macnaghten and Chilvers, 2013), an issue which is returned to in greater detail in Chapter 7. Whilst this chapter in isolation reports an inclusive appraisal in terms of specialist and interest group representation, it also provides significant opportunities to build on existing work exploring public deliberation on geoengineering technologies (e.g. Parkhill & Pidgeon, 2011; Macnaghten and Szerszynski, 2013; Corner et al., 2013; Pidgeon *et al.*, 2013) by opening up to broader framings as part of the wider DM process which is the focus of the next chapter.

Chapter 6

Citizen Strand Results and Discussion

This chapter is the second of two dedicated to the analysis and discussion of the results of the Deliberative Mapping (DM) process with reference to the wider literature. In this chapter the results of the citizen strand, composed of members of the public who participated in the first and second citizens' panels and the joint workshop, are presented. The results of this strand are compared and contrasted throughout this chapter with those of the specialist strand reported in Chapter 5. First, this chapter begins by examining the ways in which citizens framed the issue and explored the options under consideration in Section 6.1. Second, the selected discretionary and citizen-defined 'additional' options are reported, together with the appraisal criteria developed by citizen participants with which to evaluate those options alongside the core options, in Section 6.2. Third, the qualitative performance of different geoengineering and mitigation options and business as usual, is reported in Section 6.3. Fourth, the relative weighted importance of different appraisal criteria are reported together with the overall option rankings for the DM process. The chapter concludes by summarising its substantive contributions to knowledge and considering their implications.

6.1 Framing and Exploration

The citizen participants developed a series of frames through which they would later engage with geoengineering and other options for responding to climate change. These frames and the citizens' initial exploration of the options under consideration are considered respectively in Sections 6.1.1 and 6.1.2 below. Section 6.1.3 then outlines the citizens engagement with specialists during the joint workshop.

6.1.1 Issue framing

The men's and women's groups engaged in open discussion of global environmental issues with contingent differences, with the former contextualising them within the broader issue of human overpopulation as a driver and the latter within that of human resilience to change. The particular issue of climate change emerged unprompted from both groups' discussions early on, before being formally introduced by the facilitators. Both of the groups engaged with discussion of climate change through its science and uncertainty as a point of entry. However, the uncertainty aspect was approached differently, with the men's group engaging through a lens of scepticism and counter–scepticism, and the women's group engaging through a lens of trust. These lenses are consistent with recent public concerns over trust in climate science (Jasanoff, 2010), with scepticism of climate change more generally (Poortinga *et al.*, 2011) and with gender biases (Whitmarsh, 2011).

Talk of scepticism and counter–scepticism in the men's group centred around two citizens (P2, P5) who attributed climate change to mainly natural and mainly anthropogenic causes respectively. With reference to scientific observation and the so–called 'Climategate' affair, the extent and reliability of evidence was a key point of contestation: 'I still don't believe the scientists understand a lot' (P2)... 'But it's based on evidence, hard evidence' (P5). In the absence of a 'strong scientific background' (P8), public trust in the arbiters of scientific knowledge was the focus of discussions in the women's group. Politicians and the media were viewed as often overstating the risks of climate change or framing its responses in ways that served particular vested interests. The women's group also conversed about their personal experiences of weather and climate, echoing public engagements recorded in other research (e.g. Lorenzoni & Pidgeon, 2006), with older citizens recollecting observed changes within their own lifetimes.

The current economic and political systems were seen as being at the core of the climate change problem by both groups. 'Growth at all costs' (P7), 'materialistic' (P1) society and a failure 'to think long term' (P2) were all viewed as primary drivers of climate change and global environmental issues more widely. The first session concluded with a discussion of options for tackling climate change, with both groups identifying sources of renewable energy and individual actions, of which the latter constituted a moral 'responsibility' (P3, 13) for the women's group. Responsibility also played a larger role in relation to government and industry in both groups, in terms of the former's power to compel change and the latter's capacity to make change. Geoengineering was not explicitly mentioned by either group, but carbon geoengineering proposals were inadvertently referred to through afforestation in the women's group and 'natural processes on the Earth for sinking carbon dioxide... [such as] the sea' (P12) in the men's group.

6.1.2 Option exploration

The two groups were invited to explore their initial reactions to the core options under consideration, in order to develop options as well as elicit the existing knowledge and value frameworks they would later draw on to engage in appraising the options. Citizen engagement with the geoengineering options yielded completely different reactions to those found with the mitigation options. One theme was present across all of the geoengineering options: naturalness. The judgement of how natural or unnatural an option was resonates with recent public engagement work with geoengineering, which has found naturalness to be an important determinant of perception (Corner *et al.*, 2013). As with the aforementioned study, naturalness was a theme that was introduced unprompted by the citizens themselves; the research team avoided its introduction given its documented strong framing effects (Corner *et al.*, 2011).

In agreement with the study by Corner *et al.* (2013), the naturalness of geoengineering options was perceived differently by participants and in different contexts, contrasting with other research where a naturalness framing was asserted. Stratospheric aerosol injection was a complex case, simultaneously viewed as both natural in terms of its volcanic analogues and unnatural in terms of 'interference with nature' (P7). Where biochar has been viewed as a natural process in previous research, here it was perceived as unnatural for its artificial manufacture through pyrolysis (c.f. NERC, 2010). Similarly, where air capture and storage has previously been viewed as artificial and engineered, here it was perceived as natural for 'putting [carbon dioxide] back in the ground' (P4). These findings suggest that the naturalness of geoengineering options can be perceived and framed quite differently, dependent upon the aspect or phase of operation under scrutiny.

Another cross cutting theme was present across both of the carbon geoengineering options: scale. Both the physical scale and scalability were issues here, with biochar viewed as too small scale and air capture and storage as too large scale, and both viewed as difficult to scale up. This drew on other themes also raised during the discussion, primarily concerning land–use in the case of biochar and storage availability in the case of air capture and storage. For biochar, these other themes concerned the option's potential for conflict with other land uses; with citizens citing existing issues with biofuels as an analogy, and questioning whether such land could be used in better ways, such as through afforestation. Citizens also discussed the option's sustainability and possible co–benefits for agriculture. For air capture and storage, other themes explored the safety of the option's storage component and its potentially displeasing aesthetics, but also its complimentarity with other options, such as low carbon energy sources for its energy supply and the carbon market for investment return.

The other themes explored under stratospheric aerosol injection began with the issue of logic. As one citizen put it:

> 'We got into this problem by pumping lots of stuff into the atmosphere, so our solution is to pump more stuff into the atmosphere?' (P2).

This resonated with remarks made by another participant in the specialist strand of the process (B). Another citizen added that 'It's curing the symptom and not the problem' (P5). Others remarked: 'it's a little bit mad scientist' (P4) and 'We're getting into the realms of fantasy' (P9). Another important theme of exploration related to the option's possible impacts on humans and the environment, with concerns raised as to reversibility and the potential for accidents. Echoing the findings of NERC (2010), citizens raised concerns about the risk of moral hazard, whereby the use of such an option might hamper efforts in mitigation.

In contrast with the geoengineering options, citizen exploration of the mitigation options did not yield cross–cutting themes. For voluntary low carbon living one theme was most prevalent: uptake. Whilst it was seen as an option that both concerned and was accessible to everyone, it was also viewed as going 'against consumerism' (P5) and was therefore unlikely to be adopted by many. Citizen participants noted education and regulation as possible ways of overcoming this inaction, with reference to industry as a priority target. For offshore wind energy its perceived high cost and intermittent reliability were themes alongside mixed views about its environmental impacts. A low carbon footprint beyond its initial construction was contrasted with longer term environmental impacts associated with its legacy. For a new market mechanism two themes were dominant: feasibility and enforcement. Citizens were doubtful that such a mechanism could be agreed upon, let alone operate; and concerns were expressed about corruption and fairness.

Citizen exploration of business as usual focussed around three main viewpoints: that the risks of climate change brought about by this option would be serious, but humanity could adapt to some degree; that it was not an option; and that fossil fuels would be exhausted in time irrespective of climate change.

6.1.3 Citizen-specialist interaction

One of the key novelties of the DM process has been its facilitation of citizen-specialist interaction through the joint workshop. This is a distinctive feature of the approach that no other existing participatory appraisal method develops in an entirely parallel and symmetrical way. The joint workshop proved to be an important step in the process, allowing participants to substantiate and sometimes reshape many of the issues broadly identified during option exploration in the initial citizens panel (cf. Davies and Burgess, 2004). Interestingly, rather than becoming more sceptical of geoengineering after gaining further knowledge (see Spence *et al.*, 2010), some citizens became more cautiously supportive (see also Parkhill & Pidgeon, 2011). This was not because of option or issue advocacy by the specialists present, who themselves noted their moderate positions, but because reference to actual and ongoing research was made. Such reference appears to have normalised what had previously been viewed as 'fantasy' (P9) and gone some way towards meeting the acceptance 'conditions' of feasibility and efficacy outlined in Macnaghten & Szersynski (2013). Overall the citizens had engaged in a recognisably intensive learning process, but expressed their regret at not having more time or more information to complete the appraisal. This research has thus shown that citizens can effectively engage in complex issues such as geoengineering in the context of tackling climate change, and develop informed and considered judgements that are fully comparable with those of specialists.

6.2 Options and Criteria

The citizens developed a range of additional options to appraise alongside the seven core and selected discretionary options, as well as a rich diversity of criteria with which to evaluate them. These additional options and criteria are considered respectively in Sections 6.2.1 and 6.2.2 below.

6.2.1 Additional options

In addition to the core options explored in Section 6.1.2, citizens noted several additional options which were later appraised in common by the men's and women's groups or by individual participants (see Table 6.1). Citizens voted in plenary to appraise one discretionary mitigation option and one additional carbon geoengineering option in common: nuclear fusion energy and afforestation. Those additional options that were appraised only by individuals all constituted forms of mitigation, and in particular, forms of renewable energy. Echoing the specialists' rationales, these options were included either as openly favoured options, cases of particular interest, or simply to fill perceived gaps in the list of core and discretionary options. One of these was a decentralised energy strategy (A10), three were conventional forms of renewable energy (A11 - A13), and one was a proposed form of nuclear energy (A14). The addition of these six options brought the total of additional options in the DM process to 14, including one carbon geoengineering option that was independently defined in both strands (afforestation).

Table 6.1. The definitions of 'additional' options (A6 plus A10 - A14) defined and appraised by citizen participants.

Option	Definition
A6 Afforestation (Women's group)	Increasing the proportion of the Earth's land surface covered by forests.
A10 Home electricity generation (P11)	Increasing the proportion of energy provided by small-scale energy generators at home to improve energy efficiency.
A11 Hydroelectric energy (P9)	Increasing the proportion of energy provided by hydroelectric power stations.
A12 Solar energy (P4)	Increasing the proportion of energy provided by photovoltaic power stations.
A13 Wave and tidal energy (P12)	Increasing the proportion of energy provided by wave and tidal power stations.
A14 Thorium nuclear energy (P5)	Focusing research and development into the use of thorium for nuclear energy generation.

Citizen group or codes of those defining the corresponding additional options are indicated in brackets to the right.

6.2.2 Criteria groups

The citizen strand yielded a rich diversity of 32 appraisal criteria, which have been coded into 24 emergent subgroups that constitute part of 7 main criteria groups (see also Appendix 2.2.2). These groups spanned both technical and social issues, ranging from questions of efficacy, environment and feasibility to those of economics, safety, society and ethics. Concurrently, the specialist participants had developed a total of 61 criteria, which were coded into 29 emergent subgroups that constitute part of 8 main criteria groups (see Section 5.1.2). These groups mirror those of the citizens, with the exception of an absent 'safety' criteria group and additional 'political' and 'co-benefits' groups. Whilst each of these issues were addressed by both strands through different criteria groupings, their standalone development suggests their differing relative importance to each strand. A total of 93 criteria were independently developed by the two strands, of which 80 were unique. Unlike the citizens, specialists also developed a total of 23 principles, against which options would be deemed acceptable or unacceptable and ruled in or out completely, which were coded into 18 emergent subgroups that mapped onto their 8 main criteria groups. (see Figure 6.1)

A number of unique criteria subgroups emerged from within the citizen strand, spanning all of their criteria groups with the exception of feasibility criteria. Under efficacy criteria this included duration of effect, reflecting the perceived importance of an option's long term sustainability. Under environment criteria this included different option's carbon footprints and impact reversibility. Under economic criteria this included whether an option would yield a return on investments. Side effects on humans was a unique criteria subgroup developed under the unique safety criteria group. Issues of morality imperative or pursuit, potential misuse and technology availability were each unique criteria subgroups within the ethical criteria group.

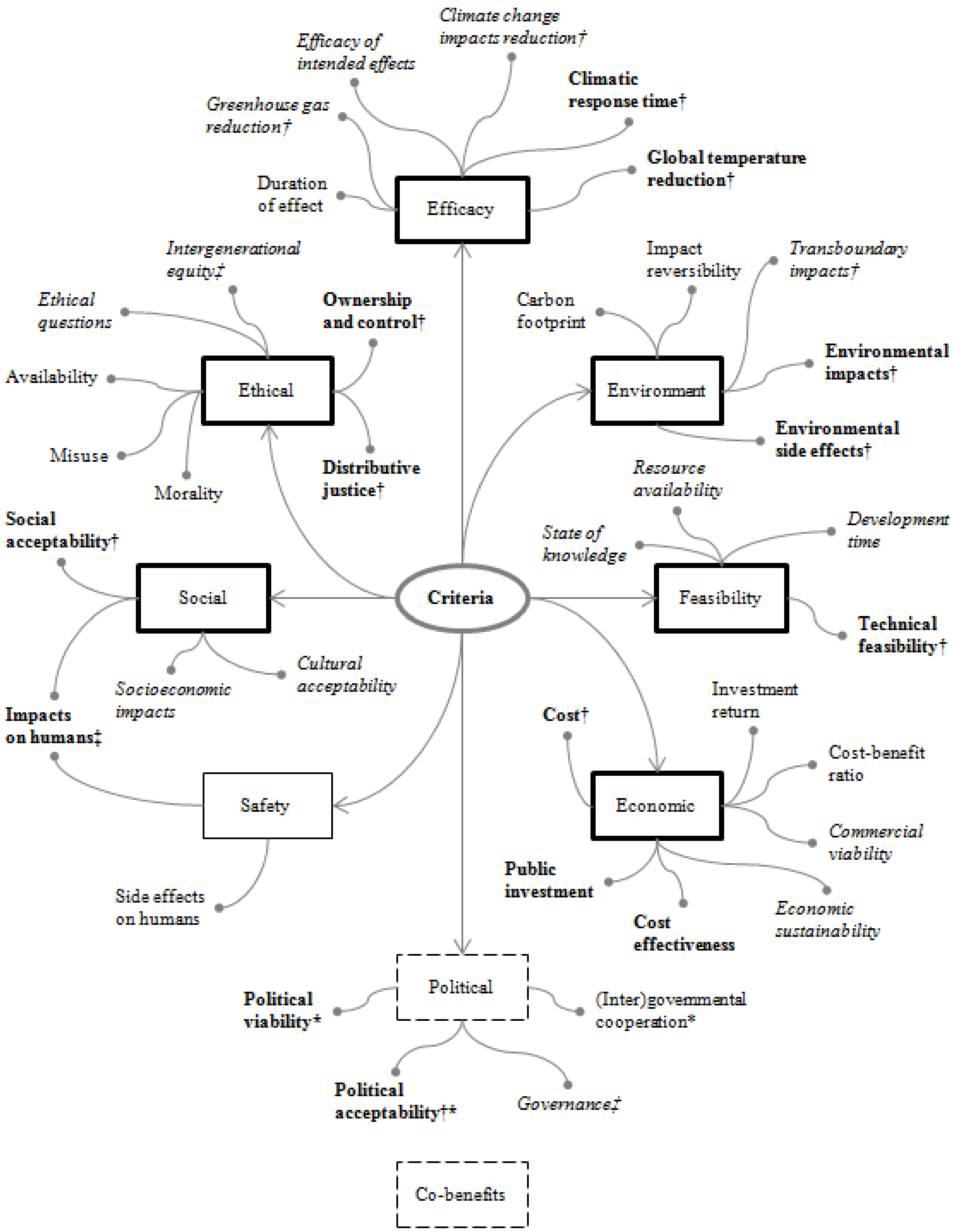


Figure 6.1. Criteria map of specialist and citizen criteria groups and subgroups. Criteria groups and subgroups in bold indicate those independently developed by both the specialists and the citizens; criteria groups and subgroups in normal font indicate those developed by citizens; and dashed criteria groups and criteria subgroups in italics indicate those developed by specialists. † indicates criteria subgroup also deployed as a principle by specialists; ‡ indicates a principle developed by specialists; * indicates criteria subgroup also developed by citizens under feasibility criteria group. The co-benefits group was developed as a lone but cross–cutting criterion by one specialist (B). The groups and subgroups are high-level groupings that do not show the full complexity of criteria and issues that lie beneath.

6.3 Option Scoring

The citizens' panels transcript datasets revealed a wealth of in-depth qualitative reasonings that underpinned the participants' scoring of option performance. These reasonings are organised around the seven citizen criteria groups in Sections 6.3.1 – 6.3.7 where they are compared and contrasted with the results of the specialist strand. Therein the performance of each of the core and common discretionary and additional geoengineering and mitigation options and business as usual is discussed respectively. The additional options appraised by individual citizen participants are not discussed here owing to partial engagements and absent reasonings during the scoring process. Overall option scoring against the criteria groups is outlined according to the rank means for corresponding criteria, and to variability between citizen perspectives determined by the rank extrema for corresponding criteria (see Appendix 2.3.2).

6.3.1 Efficacy

Of the geoengineering options, **stratospheric aerosol injection** performed most highly against efficacy criteria, despite a maximum range of variability that indicated a polarisation of citizens' perceptions. Whilst few questioned its potential for reducing global temperature, others raised concerns about the need for sustaining injections to avoid going 'back to square one' (P12) and its untested nature. This high variability mirrored that recorded in the specialist strand, but overall the option performed significantly more highly with the citizens. Both **air capture and storage** and **biochar** performed moderately, and both with a large range of variability. As with stratospheric aerosol injection, air capture and storage also displayed the maximum range of variability, with citizens citing its technical immaturity in unison with the specialist strand. Also in harmony with the specialist strand, the likely scale of biochar implementation was seen as 'too small to make an impact' (P6). The one common additional option, **afforestation**, scored highly but with a high degree of variability. This was in contrast with the one specialist who appraised the option in the specialist strand (E), where it scored poorly with little uncertainty.

Voluntary low carbon living was the best performing mitigation option, and the highest performing option overall against efficacy criteria. However, a moderate range of variability revealed differing perceptions about the likelihood of its uptake. This reasoning echoed that of those in the specialist strand, but proved to be a far more influential factor with the specialists where by contrast the option scored very poorly with some variability. **Offshore wind energy** also performed very highly and with a similar range of variability. The fact that the option was already in operation earned the option its score, but some questioned its efficiency. These reasonings also mirrored those aired in the specialist strand, but there it instead resulted in a moderate performance with little variability. A **new market mechanism** performed poorly against efficacy criteria, and with a large range of variability. Its perceived slow rate of progress and ability to effectively sustain business as usual amongst developed nations were cited as problems. Interestingly, one citizen said with respect to both the new market mechanism and offshore wind energy that they:

> '...would stop people using as much carbon, but all the CO_2... is still up there. That doesn't include anything about removing CO_2 does it?' (P1).

This identifies the issue of mitigation options not undoing already emitted CO2 and the corresponding level of climate change to which the planet is already committed (IPCC, 2013). The options' poor overall performance and high variability was echoed in the specialist strand. The one discretionary option, **Nuclear fusion energy**, scored very highly against efficacy criteria with some variability, contrasting with a moderate and highly variable performance in the specialist strand.

In agreement with the specialist strand, **business as usual** performed very poorly against efficacy criteria, and was the worst performing option overall, with little variability. One citizen noted that:

> 'It's going to be very unlikely [to reduce global warming]. But the likelihood of us going to carry on with business as usual... That's a scary possibility' (P5).

6.3.2 Environment

Mirroring its performance in the specialist strand, **biochar** was the highest performing geoengineering option against environmental criteria, which scored moderately with a large range of variability. With reference to a possible co-benefit, one citizen stated:

> 'I don't see what the negative impacts could possibly be. In fact, you actually benefit in one way because you get a little bit of free fertiliser' (P4).

On the other hand, another drew attention to environmental concerns about possible side effects from the pyrolysis process needed to produce the biochar. **Air capture and storage** also performed moderately, for environmental benefits associated with its reduction in CO_2 concentration. However, a large range of variability emerged as citizens raised concerns about possible leakages and, ironically, its carbon footprint. Several citizens also made comparisons with offshore wind energy, highlighting displeasing aesthetics and risks to wildlife. In mild contrast, the option scored relatively highly in the specialist strand. **Stratospheric aerosol injection** scored very poorly with a large range of variability, much as it did in the specialist strand. Whilst it was viewed as potentially curbing the impacts of climate change, one participant astutely summarised that 'This will have negative impacts on the environment no matter what happens' (P1). Citizens were concerned with its potential for drastically altering weather patterns, whilst the women's group noted its unnaturalness and 'meddling' (P3, P13) with the Earth system. Uncertainty also played a large role in citizens scoring of this option, with one advancing a precautionary stance:

> 'We just don't know, so I'd err on the side of caution saying it's very likely we're going to have problems with this particular system' (P4).

Afforestation scored very highly, echoing Specialist E who appraised the option in the specialist strand, but in contrast it did so with a high degree of variability.

Of the mitigation options, **voluntary low carbon living** was the best performing option, and the highest performing option overall, performing very highly against environmental criteria. Very little variability emerged as citizens found it difficult to think of any negative impacts, save for those that could be unforeseen, mirroring the results of the specialist strand. **Offshore wind energy** scored highly, but with the maximum range of variability. Drawing parallels with air capture and storage, citizens raised concerns about the option's carbon footprint, displeasing aesthetics and risks to wildlife. The option also scored highly in the specialist strand, but with less variability. A **new market mechanism** performed moderately, but also displayed the maximum range of variability owing to uncertainties over its perceived ability to change or maintain business as usual. This variability was echoed in the specialist strand, whilst overall the option scored more highly. **Nuclear fusion energy** scored moderately, but with a high degree of variability, contrasting with a higher performance in the specialist strand.

Echoing the results of the specialist strand, **business as usual** itself performed very poorly against environmental criteria with the citizen participants, and was the worst performing option overall, with very little variability.

6.3.3 Feasibility

Biochar and **stratospheric aerosol injection** were the highest performing geoengineering options, which both scored moderately with a large range of variability. In agreement with the specialist strand, biochar was widely viewed as limited by its scalability, despite its feasibility in principle. Despite being denounced as unnatural under environmental criteria, here stratospheric aerosol injection was described as 'natural' (P13) in the women's group whilst discussing its demonstrable feasibility through volcanic analogues. However, extensive testing was highlighted as an essential prerequisite for full scale deployment. Including political criteria under their feasibility criteria group, citizens concurrently viewed the option as politically unacceptable and in need of international cooperation. In contrast, the option scored more poorly in the specialist strand. **Air capture and storage** performed poorly with a high degree of variability relating to a lack of demonstrable feasibility at scale and perceived high maintenance. The option performed more moderately in the specialist strand. **Afforestation** scored moderately for its existing practice, but with a high degree of variability for the slow rate of tree growth and associated CO_2 sequestration, and for its potential conflict with different land-uses. In contrast, afforestation scored much more highly with the specialist who appraised the option.

Offshore wind energy was the best performing mitigation option, and the highest performing option overall against environmental criteria, owing to its existing operation. This echoed the results of the specialist strand where it scored similarly highly. Also echoing the specialist strand, **voluntary low carbon living** scored highly too, with some variability relating to different citizens' optimism or pessimism regarding its uptake. A **new market mechanism** performed very poorly, and was the worst performing option overall, with a high range of variability. Whilst its existing operation in the European Union (EU) was noted, its feasibility further afield was in doubt owing to perceivably unattainable but required political agreements. The option was seen more positively in the specialist strand, where it scored moderately, but with a high degree of variability. **Nuclear fusion energy** scored moderately with a moderate range of variability relating to its perceived development time: 'It's always fifty years away' (P5). The option was more pessimistically received in the specialist strand, but with a similar range of variability.

Business as usual performed moderately against feasibility criteria, with variability that covered the maximum range. Such variability arose from citizens differing engagements with this criteria group, with some citing the option's inherent feasibility in that it was already in operation, whilst others noted its inability to tackle climate change. This mildly contrasted with the specialists' engagement with the option, where it was viewed as more highly feasible.

6.3.4 Economics

Of the geoengineering options, **stratospheric aerosol injection** performed most highly against economic criteria, scoring moderately for being viewed as 'cheap' (P2) despite showing a maximum range of variability. This echoed the results of the specialist strand. Both **biochar** and **air capture and storage** performed moderately also, and both with a large range of variability. The latter carbon geoengineering proposal scored marginally worse than the former, owing to perceived high construction and maintenance costs. Biochar scored similarly moderately in the specialist strand, whilst air capture and storage performed more poorly. Echoing the results of the specialist who appraised **afforestation**, the option scored moderately with some variability where the long term benefits were seen to outweigh the initial costs.

Voluntary low carbon living was the best performing mitigation option, and the highest performing option overall, yet still performing only moderately against economic criteria. A moderate range of variability revealed some anticipated costs in government-led social marketing campaigns and disagreements as to whether such an options would save, or cost, money for individuals. One citizen noted that improved energy efficiency could save energy without the need for relying on peoples' voluntary action or inaction. In contrast, the option scored more highly in the specialist strand. Echoing the results of the specialist strand, **offshore wind energy** performed moderately with a moderate variability range. Whilst the option was viewed as affordable now, albeit through subsidies, ongoing maintenance costs limited its performance. A **new market mechanism** also performed moderately with moderate variability, but this contrasted with a higher performance in the specialist strand. Citizen participants viewed the length of time needed to develop and agree a new market mechanism as an expensive endeavour. **Nuclear fusion energy** scored moderately with a large range of variability surrounding its existence only as a 'concept' (P2). Similar variability was recorded in the specialist strand amidst a poorer overall score.

In contrast with the specialist strand where it was scored poorly for its indirect climatic impacts on the economy, **business as usual** performed moderately showing a maximum range of variability. Whilst viewed as cheap to 'just carry on' (P1) citizens also highlighted the likely escalating costs associated with living with the impacts of climate change.

6.3.5 Safety

Developed as a distinct criteria group only by the citizen strand, safety criteria did not benefit the appraisal of **stratospheric aerosol injection**, against which it was the worst performing geoengineering option. Referencing risky changes to weather patterns, one citizen summarised:

> 'It's just the whole fact that we're putting up some dangerous chemicals into the atmosphere which I think is a process we don't fully understand' (P2).

Interestingly discussion of the naturalness of stratospheric aerosol injection surfaced again in the women's group under this criteria group. Here two citizens drew a distinction between the naturalness of the option's process and of its content:

> '...artificial interference as it were' (P10).

> 'Although it's not artificial material' (P13).

Biochar was the highest performing geoengineering option, scoring highly with a large variability range. The option was perceived positively in terms of its propriety for use in home gardens, but negatively in terms of risks linked to its pyrolysis component. The option was also compared with a local, controversial waste incinerator project (BBC, 2013). **Air capture and storage** performed moderately, but with a maximum range of variability. **Afforestation** scored very highly against safety criteria with little variability.

With no apparent safety issues, **voluntary low carbon living** performed very highly, and was the best performing option overall against safety criteria. **Offshore wind energy** also scored highly. A **new market mechanism** scored moderately, but with a maximum range of variability. **Nuclear fusion energy** scored moderately but with a large range of variability.

Business as usual performed very poorly, and was the worst performing option overall against safety criteria. However, a large range of variability revealed differences in citizens' time horizons for concern, with those concerned with nearer term safety less concerned than those concerned with longer term safety. Citizens' views also differed with respect to the capacity for humans to adapt to climate change. For example, two participants exchanged:

> 'We're going to be here for a long time I reckon' (P10).

> 'I'd like to believe that but I've seen too many world ending films lately' (P3).

6.3.6 Society

Biochar was the highest performing geoengineering option against social criteria, scoring moderately with some variability. Citizens viewed the performance of biochar here, and with other options under this criteria group, as likely to be determined by public understanding, or perception. With biochar, citizens thought the idea of burning biomass, understood as trees, to be counterintuitive and that it would be met with public hostility. On the other hand, dependent upon its scale of deployment it was viewed as unlikely to affect peoples' lives and could even be used as fertiliser on a personal basis. By contrast, this option was scored more highly in the specialist strand. **Air capture and storage** performed poorly with a large range of variability associated with displeasing aesthetics and low public awareness. Similar concerns were raised in the specialist strand, whilst instead performing moderately. **Stratospheric aerosol injection** performed poorly, in line with the very poor score attributed in the specialist strand, and was the worst performing option overall with a maximum range of variability. In its most optimistic appraisals citizens claimed it could be 'easy to sell' as a volcanic analogue, but that considerable uncertainties would override that. The only circumstances under which the option was viewed as likely to be acceptable were when 'things start to get worse' (P5) or are 'looking bleak' (P2). On the other hand, it was argued that 'the media would grab hold of sulphate particles and tear it to shreds' (P2). The same citizen also questioned the logic of the option's premise:

> 'We got into this mess by pumping chemicals up there, why do we now want to pump more particles up there?' (P2).

Afforestation performed highly, much as it did with the specialist who appraised the option, with a moderate range of variability related to the possibility for conflict with land owners.

Of the mitigation options, **offshore wind energy** was the best performing option, and the highest performing option overall, performing highly against social criteria. Whilst the option was viewed as uncontroversial in that it was a familiar technology, citizens again drew a parallel with air capture and storage, citing aesthetic concerns. This echoed the results of the specialist strand. **Voluntary low carbon living** also scored highly, much as the option did in the specialist strand, albeit with a large range of variability relating to the extent to which it would impede lifestyles and its appeal across different cultures. In line with the specialist strand, a **new market mechanism** performed moderately with a large variability range. Whilst it was viewed as an option that didn't directly impact upon people, indirect impacts akin to financial crises were cited as concerns. **Nuclear fusion energy** scored moderately with a large range of variability, contrasting with a more pessimistic performance in the specialist strand.

Business as usual performed moderately against social criteria, much as it did in the specialist strand, with a large range of variability. Whilst it was viewed as clearly being acceptable to the public by its perseverance, citizens believed that few would advocate it as a course of action.

6.3.7 Ethics

Biochar and **air capture and storage** both performed moderately against ethical criteria, each with a maximum range of variability. Biochar was viewed as largely unproblematic in both the citizen and specialist strands, save for its imposition on nearby people. Variability around air capture and storage was also drawn from debates around its location, as well as about different nations' access to the technology and where investment would come from. Interestingly, one participant added that in order for each of the geoengineering options to get 'payback' on the investments, they should be coupled with a carbon market mechanism (P2). In contrast, air capture and storage scored poorly in the specialist strand. **Stratospheric aerosol injection** performed poorly, with a large variability range. Contested ethical issues quickly arose, with one citizen saying 'It'd be fair if it went everywhere' (P3) with a retort from another saying 'what if someone didn't want it above them?' (P1). Other citizens noted the need for, and unlikely, attainment of multilateral agreement prior to deployment:

> 'How are you going to get the world to agree that we're going to shoot things up there' (P13).

Another voiced concerns over the possible unilateral consequences: 'Country A decides what's going to happen... and country B suffers' (P4). This mirrored the results of the specialist strand, whilst there was less variability amongst the specialists in reaching this performance. **Afforestation** scored moderately with a high degree of variability related to land-use conflict.

Offshore wind energy was the best performing mitigation option, and the highest performing option overall against ethical criteria, scoring highly with a moderate range of variability owing to its imposition on certain locations and people. In contrast, the option scored moderately with specialists. **Voluntary low carbon living** also scored highly, much as it did with specialists, despite a maximum range of variability. Its availability to everyone was seen positively, but uptake by some and not others was viewed as unfair. In agreement with the specialist strand results, a

new market mechanism performed very poorly and was the worst performing option overall, with very little variability. Citizens cited concerns over the fairness of credit allocations and risk of abuse. **Nuclear fusion energy** scored moderately with a high degree of variability related to the prospect for market domination:

> 'As soon as nuclear fusion becomes viable, do you not think the Shell's and the BP's will just come buy up the technology and completely flood the industry and own it and make loads of money' (P3).

Business as usual also scored poorly, much as it did in the specialist strand, with a large range of variability relating to its unfair distribution of risks on the world's poor and on future generations.

6.4 Criteria Weighting and Option Ranking

Subsequent to option scoring the citizen participants were invited to assign weightings to their criteria to indicate their relative importance. These weightings, together with the overall option rankings for the men's and women's groups, are considered in Sections 6.4.1 and 6.4.2 below. In response to participant requests, an additional quantitative data feature related to option diversity was added at the end of the second citizens' panel, which is considered in Section 6.4.3.

6.4.1 Criteria weighting

The seven criteria groups developed by citizen participants are ranked according to their mean weightings for both of the groups and presented alongside those rankings for each of the specialist sectors for comparison in Table 6.2. The mean weightings for each criteria group were less similar than those for the specialist strand (within 18.3% of one another), but shared a considerable variation between the individual citizen participants. In spite of this, the mean weightings were independently very consistent between the two groups (within 5.4% of one another), unlike the variation recorded between the specialist sectors. Indeed, the groups showed the same rank order with the exception of the two lowest ranking criteria, social and ethical, where men rated the former higher than the latter and vice versa. Table 6.2 shows no drastic alteration in the overall criteria rankings from those initial, specialist sector rankings reported in Table 5.3 in Chapter 5. Efficacy, environmental and economic criteria remain the three most heavily weighted issues respectively. Feasibility criteria replace social criteria as the fourth most heavily weighted, whilst social criteria replace feasibility criteria as the fifth. Ethical criteria were weighted as less important by citizen participants, causing the option to drop in ranking. This contrasts sharply with other DM processes, where ethical and social criteria have ranked much more highly (see Davies *et al.*, 2003; Burgess *et al.*, 2004).

Table 6.2. Criteria group weightings by specialist sector and weighted order.

Criteria group	Men	Women	Academic	Civil society	Industry	Government
Efficacy	1	1	3	4	-	1
Environmental	3	3	**2**	(2)	4	3
Economic	4	4	7	(1)	2	2
Feasibility	2	2	8	-	1	5
Social	6	7	5	**3**	(3)	6
Political	-	-	6	(5)	-	(4)
Safety	5	5	-	-	-	-
Ethical	7	6	4	(6)	-	-
Co-benefits	-	-	(1)	-	-	-

Criteria are in descending order by mean weight. Orders displayed in brackets were only used by one participant, and those displayed in bold are the highest ranking criteria notwithstanding those that were only used by one participant.

The citizen participants gave comparatively high weighted attention to the more technical sets of criteria. Echoing the weighting distribution in the specialist strand, efficacy criteria were weighted most highly amongst the citizen participants, with 8 out of the 12 participants giving the group their highest or joint highest weighting. Feasibility and environmental criteria were the second and third highest weighted groups respectively, with 2 participants giving each group their highest or joint highest weighting. Economic and safety criteria were the next most heavily weighted, with the former receiving the highest weighting from 1 participant, but also the lowest or joint lowest weighting from 3 others; whilst the latter received the joint lowest weighting from 1 participant. Social and ethical criteria were weighted the least highly. Whilst social criteria were given the joint highest weighting by 1 participant, the group received the lowest or joint lowest weightings from 6 participants, of which 3 gave the group no weighting at all. Ethical criteria were given the joint lowest or lowest weighting by 7 participants, of which 1 gave the group no weighting at all.

6.4.2 Option ranking

The range of scores in the citizens' appraisals allows for an overall mapping of option performance (see Figure 6.2). Option rankings were strikingly similar across both the men's and women's groups, with voluntary low carbon living and offshore wind energy performing much better than the other core options. Whilst clear patterns of consistency can be observed, so too can a patterns of difference. First, a distinction between the overall performance, and range of scores, of the 'technological' geoengineering proposals and biochar can be clearly drawn in the men's group, and to a lesser extent with the women's group, with air capture and storage and stratospheric aerosol injection performing markedly worse than biochar and with a larger range. Second, the rank order of air capture and storage and stratospheric aerosol injection are reversed, with the former viewed more favourably by the women's group and the latter by the men's group. This is reflected in part in the qualitative data where whilst both groups were highly concerned by environmental, social and ethical issues surrounding the impacts and attainment of consent for stratospheric aerosol injection, the men's group were more concerned than the women's group about the potential costs of air capture and storage. Third, the men's group shows a greater range of scores than the women's group, reflecting dynamics in the latter group that sought consensus amongst the participants by converging their scores post–deliberation. Fourth, a new market mechanism performs far worse in the women's appraisal, most likely because of some degree of misunderstanding, recorded in the transcripts, as to what the option entailed.

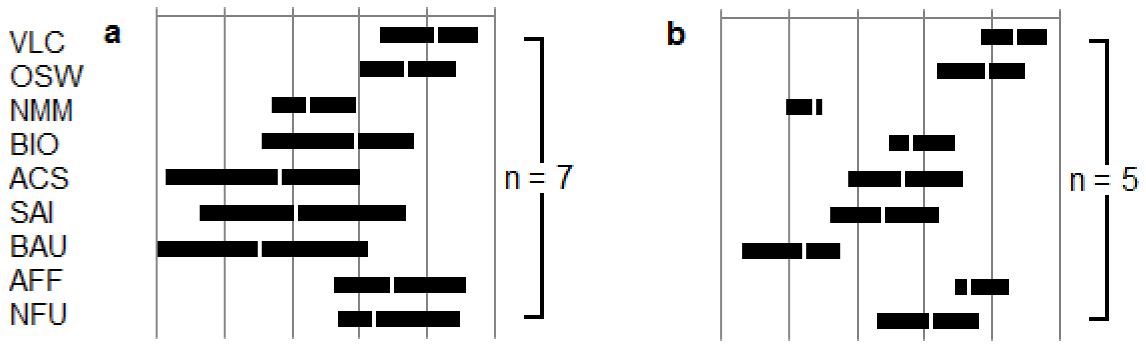


Figure 6.2. Citizens' aggregate final rankings of core options plus one additional option and one discretionary option selected and appraised by the men's group (panel a) and the women's group (panel b). Acronyms: voluntary low carbon living (VLC); offshore wind energy (OSW); new market mechanism (NMM); biochar (BIO); air capture and storage (ACS); stratospheric aerosol injection (SAI); business as usual (BAU); afforestation (AFF); nuclear fusion energy (NFU). Notes: frequency of participants appraising (n) indicated to the right of the graphic. Performances increase on an arbitrary subjective scale to the right. Bar length represents the range between the most optimistic mean score of the corresponding participants and the most pessimistic mean score of the corresponding participants. The white bar dissecting the ranges is the grand mean for the corresponding participants.

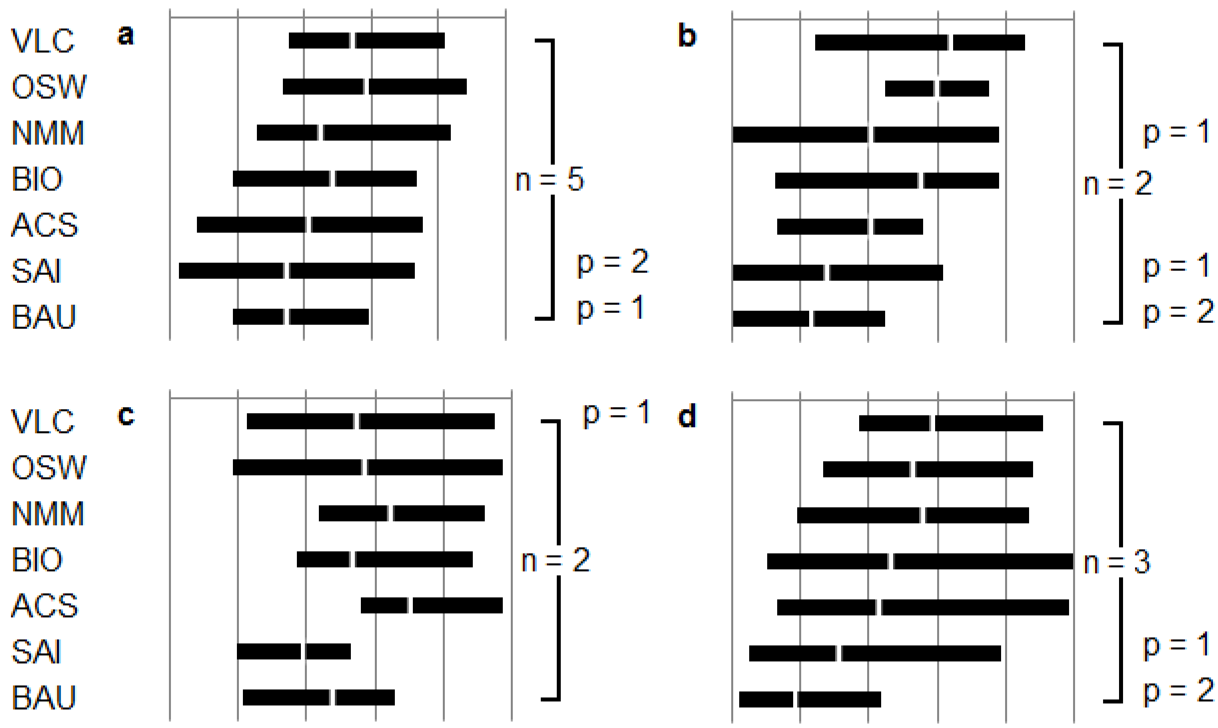


Figure 6.3. Academic (panel a), civil society (panel b), industry (panel c) and government (panel d) experts' and stakeholders' aggregate final rankings of core options appraised by all participants. Acronyms: voluntary low carbon living (VLC); offshore wind energy (OSW); new market mechanism (NMM); biochar (BIO); air capture and storage (ACS); stratospheric aer-

osol injection (SAI); business as usual (BAU). Notes: frequency of participants appraising (n) and ruling them out on principle (p) indicated to the right of the graphic. Performances increase on an arbitrary subjective scale to the right. Bar length represents the range between the most optimistic mean score of the corresponding participants and the most pessimistic mean score of the corresponding participants. The white bar dissecting the ranges is the grand mean for the corresponding participants.

By way of comparison, the mapping of option performance for the specialists' appraisals is shown in Figure 6.3, grouped by participant sector (academic, civil society, industry and government). The key difference between these specialist actor-types is that the industry sector represents a reversal of the otherwise uniform pattern. Here, the carbon geoengineering option air capture and storage is the 'lead' option with mitigation options trailing behind, in contrast to most other specialist participants. Despite this, in comparing Figures 6.2 and 6.3, it can be seen that the overall ranking of options reveals a remarkable degree of consistency between different groups on both the citizen and specialist strands of the DM process. The following list details the 'highest', 'lowest' and 'middle' scoring core and discretionary options across these appraisals within the process, where core options appraised by all process participants are shown in bold and where (DC) indicates a discretionary option appraised by all citizens and (AC) indicates an additional option appraised by all citizens and (DS#) indicates a discretionary option appraised by a specified number of specialists. Additional options that were appraised by individual participants are not included here.

The consistency between strands is made all the more remarkable, and all the more robust, by its emergence from a process that sought to map divergent perspectives. It shows three 'highest' options, comprising mitigation options and one carbon geoengineering proposal, which clearly appear to perform better than the others:

- **Voluntary low carbon living** ranked highest in both groups of citizens and for the specialists as a whole, and for the civil society and government sectors. However, Specialist I ruled this option out on feasibility grounds.
- **Offshore wind energy** ranked second highest in both groups of citizens and for the specialists as a whole, and it ranked highest for the academic sector.
- Afforestation (DC) ranked third highest in both groups of citizens. The option was also advanced as an additional option by Specialist E, where the option too scored highly.

It also shows four 'lowest' options, comprising two solar geoengineering proposals and one carbon geoengineering proposal, which clearly appear to perform worse than the others:

- **Stratospheric aerosol injection** ranked third lowest in both groups of citizens and second worst for the specialists as a whole, and for the specialist sectors, except where it ranked worst for the industry sector. Specialists A, B, G and K ruled this option out on efficacy, environment, political, social, ethical and co-benefits grounds.
- **Business as usual** ranked lowest in both groups of citizens and for the specialists as a whole, and for the specialist sectors, except where it ranked second lowest for the industry sector. Specialists E, F, G, J and K ruled this option out on efficacy, environment, social and ethical grounds.
- Iron fertilisation (DS5) ranked lowest of the discretionary options for specialists. Participant G ruled this option out on efficacy, environment, social and ethical grounds.
- Space reflectors (DS3) ranked second lowest of the discretionary options for specialists. Specialist E ruled this option out on economic grounds.

The overall performance of the remaining eight 'middle' options is more ambiguous:

- **New market mechanism** ranked moderately with the men's group and poorly with the women's group, but third highest for the specialists as a whole, and moderately across the sectors. However, specialist G ruled this option out on efficacy, environment, social and ethical grounds.
- **Biochar** ranked third highest for both groups of citizens, but moderately overall and for the specialists as a whole, and across the sectors.
- **Air capture and storage** ranked poorly with the men's group and moderately with the women's group, and moderately for the specialists overall, and it ranked highest for the industry sector.
- Nuclear fusion energy (DC, DS3) ranked highly for both citizens panels and moderately for the specialists, towards the lower end of the 'middle' ranking discretionary options.
- Nuclear fission energy (DS3) ranked moderately for the specialists.
- Coal energy with carbon capture and storage (DS3) ranked moderately for the specialists, towards the higher end of the 'middle' ranking discretionary options.
- Carbon tax (DS4) ranked moderately for the specialists, towards the higher end of the 'middle' ranking discretionary options.
- Cloud albedo enhancement (DS4) ranked moderately for the specialists.

6.4.3 Option diversity

During the course of the second citizens' panel one participant (P3) proposed an additional exercise: to undertake an assessment of the importance of the individual options in responding to climate change relative to the overall mix of options under consideration. Conveyed as the relative allocation of 'eggs to baskets', this proposal gained some interest amongst the other participants and presented an interesting opportunity to study the role of diversity and to allow citizens to engage with ruling out options on principle by their exclusion. In the spirit of responsiveness to participant needs, and given the recognised importance of option diversity in society discussed in Chapter 2, and the influential role of diversity in steering the selection of options for inclusion within the process, this proposal was taken forward as a 'bolt-on' at the end of the panel. In this exercise, participants were invited to distribute ten 'eggs' amongst the core options, excluding business as usual, to indicate the importance of those options in responding to climate change. This measure of importance drew on the performance of the options across the ensemble of criteria developed and deployed by the citizens.

A simple but somewhat robust non-parametric quantitative measure of diversity is used to determine the portfolio diversity of options for responding to climate change in each participants' mix. The 'dual concept' (Junge, 1994) Shannon-Wiener Index (Shannon & Weaver, 1962), popularly used to determine species diversity in ecological research, accounts for two of the three core concepts of diversity: variety (the number of options in the portfolio) and balance (the apportionment of options in the portfolio) (Stirling, 1998b) (see Equation 6.1), and has been successfully used in other contexts such as genetically modified crops (see Stirling & Mayer, 1999).

$$H' = - \sum_{i=1}^{S} p_i \ln p_i \qquad [6.1]$$

where H' is the diversity index for the mix of options, S is the number of options in the mix, p_i is the proportional reliance on the i^{th} option and ln is the natural logarithm.

The third core concept of diversity, disparity (the difference between options in the portfolio), is already addressed through its explicit attention during the initial selection of diverse options for appraisal in the process.

The results of this simple, but interesting, addition to the DM process are conveyed in Figure 6.4. The most striking result is that an overwhelming majority of the options that form part of the different mixes are mitigation options (77% overall), whilst significantly fewer are geoengineering proposals (23% overall). Indeed, the only two options to form part of every mix were the voluntary low carbon living and offshore wind energy options. Three relative tiers of diversity emerge from the results: high diversity (H' = 1.28 - 1.71) for which 5 participants showed an affinity, medium diversity (H' = 0.78 - 1.05) for which 3 participants showed an affinity, and low diversity (H' = 0.00 - 0.43) for which 4 participants showed an affinity. None of the participants opted for no diversity, whilst three opted for low variety mixes made up of the two best performing options: voluntary low carbon living and offshore wind energy. Whilst all of the participants expressed some affinity for variety, none included all of the six available options in their mix.

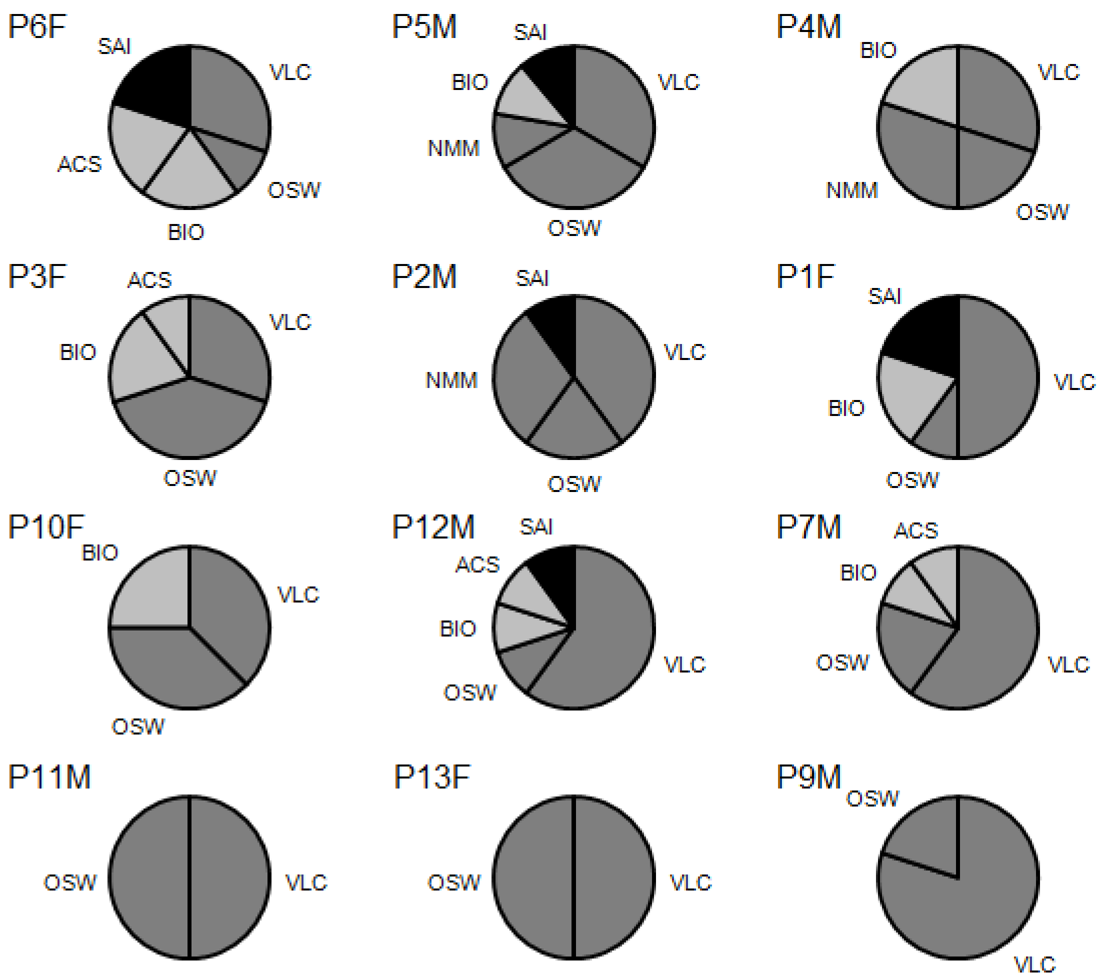


Figure 6.4. Diverse mixes of core options favoured by citizen participants, ranked from highest to lowest. Acronyms: voluntary low carbon living (VLC); offshore wind energy (OSW); new market mechanism (NMM); biochar (BIO); air capture and storage (ACS); stratospheric aerosol injection (SAI). Panel codes depict citizen participant number (e.g. P5) plus gender (e.g. M). Carbon geoengineering proposals are shown in light grey; solar geoengineering proposals are shown in black; and mitigation options are shown in dark grey.

Whilst four of the participants showed a preference for low diversity mixes, the remaining eight showed a preference for relatively medium or high diversity mixes. This suggests that most of the participants demonstrate some support for the idea of deliberate diversification of options for responding to climate change. This diversity involves the inclusion of the poorer performing options, a new market mechanism (included 3 times) and two geoengineering proposals: air capture and storage (included 4 times) and stratospheric aerosol injection (included 5 times). With one exception, this latter option was not included in any mix without the presence of other geoengineering proposals. Biochar held a more privileged role in the mixes than the other geoengineering proposals, being included 8 times. Interestingly, 9 participants included some form of geoengineering as part of their mix of options for responding to climate change. This hedging is perhaps not to be unexpected given the manifold option and issue uncertainties that emerged during the option scoring process.

Given the improvised nature of this additional exercise, these findings should be interpreted with caution. These mixes do not include the additional options proposed by the citizen participants, nor do they include other options for responding to climate change not included in this study. It does, however offer an interesting preliminary insight into the role of option diversity in responding to climate change, something that should be pursued in future research, and with greater attention to possible trade-offs between diversity and option performance (Stirling, 2007b).

Conclusions

This chapter has analysed and discussed the results of the citizen strand of the DM process, opening up of the diverse framings, knowledges and pathways that bear upon this most complex of issues to a degree that no other appraisal, analytic or participatory, has done before. First, the capacity of the DM process capacity to allow citizens' to frame the problem themselves has produced a broader diversity of resonant problem framings from which to conceptualise the issue, including overpopulation and human resilience to change, issues of scepticism and trust in science, and deep flaws in incumbent economic and political systems. Second, it's recognition of alternatives to geoengineering, spanning climate change mitigation strategies and adaptation through business as usual, in addition to allowing for citizens' to develop their own ideas, has provided a much more complete selection of options to consider. Third, by providing a more diverse and inclusive range of perspectives it has produced a greater scope of criteria with which to scrutinise and appraise those options, which in turn has exposed different performance scores and their manifold uncertainties. As a direct consequence of this approach a fundamentally different view of geoengineering has emerged, building on the findings of Chapter 5, with geoengineering options performing lower than their mitigation counterparts. In particular, stratospheric aerosol injection has once more been shown to perform very poorly, in stark contrast to the positive evaluations of this option found in many existing appraisals, including studies of public perception (e.g. Mercer *et al.*, 2011) and expert-analytic assessments (e.g. Lenton & Vaughan, 2009; Bickel & Lane, 2009; Fox & Chapman, 2011).

Concurrently a number of findings from our DM experiment are consistent with and advance those of other research into public engagement with geoengineering. The widespread uncertainties and risks involved in geoengineering, mapped here by proxy in option performance ranges and qualified by participant reasonings, are a common feature of participant discourse (e.g. NERC, 2010). Similarly, how natural geoengineering proposals appear, despite sometimes being viewed here as both natural and unnatural in different issue contexts, is a common lens through which perceptions are formed (e.g. Corner *et al.*, 2013). In accord with Macnaghten & Szersynski (2013), we do not find the binary 'supporters' and 'detractors' of geoengineering recorded in Mercer *et al.* (2011), but instead find a rather more nuanced set of positions of varying levels of support or opposition under different criteria, issues and future possibilities. These positions can be understood as conditions for acceptance, expanding on those outlined in Macnaghten & Szersynski (2013) relating to feasibility (Condition 1), side-effects (Condition 2), efficacy (Condition 3) and political (Conditions 4 and 5) criteria, and also emphasising conditions pertaining to broader environmental, economic, safety, social and ethical criteria. Expansion of conditions and criteria to include more plural normative social conditions would likely only decrease the already noted implausibility of their being met for solar geoengineering technologies.

It is clear from the findings of this chapter, and of Chapter 5 before it, that no option for tackling climate change presented here or elsewhere represents a panacea, either in terms of their efficacy or any other criterion. Each option has raised unique issues with diverse perspectives that have resulted in different ranges of performance and uncertainty, meaning that there is a need to discriminate between them. This is not to say that geoengineering proposals should be appraised in isolation, which would only serve to close down their appraisal, but to appraise them as discrete options alongside alternatives. The findings suggest that reflexive appraisal approaches such as DM will form a vital part of broader ambitions to build more anticipatory, inclusive, responsive and responsible ways of governing emerging technologies such as geoengineering (Guston & Sarewitz, 2002; Owen *et al.*, 2013; Stilgoe *et al.*, 2013; Macnaghten & Chilvers, 2013). Recent geoengineering controversies have already highlighted the need for anticipatory appraisal, which the DM process actively attends to in an inclusive and reflexive manner. These features will help to build the responsiveness of geoengineering governance to changing natural and social conditions and expert, stakeholder and public knowledges and values. It is these broader issues of responsible innovation and governance that we turn to in Chapter 7.

Chapter 7

Implications for Geoengineering Governance

Following on from the analyses of the specialist and citizen strands of the Deliberative Mapping (DM) process detailed in Chapters 5 and 6 respectively, this third empirical, and overall penultimate, chapter of the thesis presents a synthesis discussion of the process' implications for governance. Drawing on qualitative data from across both strands of the process, including the previously unexamined process evaluations undertaken by the participants and the specialists' 'foresight' exercise (see Section 4.2.2), these implications are discussed on three levels. First, an evaluation of the DM process itself is undertaken in order to determine its performance and its implications for the conduct of future participatory appraisals and how they relate to governance. Second, an evaluation of how the DM process relates to wider systems of governance is undertaken to determine its anticipatory, reflexive, inclusive, and responsive contributions towards realising ambitions for broader frameworks of responsible innovation. Third, four propositions for the governance of geoengineering research and development are outlined before a consideration of how such recommendations could be implemented. The chapter concludes by summarising its substantive contributions to knowledge and by considering their implications.

7.1 Procedural Evaluation

This thesis has built upon decades of the successful development and application of DM and its constituent appraisal methods, Multi-Criteria Mapping (MCM) and Stakeholder Decision Analysis (SDA), in the anticipatory appraisal of other analogous emerging sciences and technologies including genetically modified organisms (Stirling & Mayer, 2001), medical transplant technologies (Davies *et al.*, 2003), and energy technologies (Stirling, 1994; Chilvers & Burgess, 2008), as well as more conventional but complex issues such managing legacy radioactive waste (Burgess *et al.*, 2004) and forms of environmental planning (Burgess, 2000). The extent to which these other issues can be considered analogous here, however, is a critical point for reflection.

The issue(s) of focus in this thesis, geoengineering and climate change, are arguably more complex than those aforementioned, contending with far greater spatial and temporal scales. Moreover, the process has been significantly scaled down from previous incarnations of the method, presenting both opportunities and trade-offs in doing so. It is therefore imperative that the performance of the DM process itself be reflected upon, in order to extract implications for the conduct of future participatory appraisals of this nature. Section 7.1.1 outlines the methodological approach used to evaluate the effectiveness of the process, whilst Section 7.1.2 critically examines the performance of the process with reference to the participants' evaluations and personal reflection.

7.1.1 Evaluation method

There exists an extensive literature devoted to establishing what constitutes effective participatory appraisal that has derived evaluative criteria from a range of normative theoretical, policy procedural and grounded perspectives (e.g. Webler, 1995; Stern & Fineberg, 1996; Rowe & Frewer, 2000; Burgess & Clark, 2006). A significant consensus has now been established around seven key effectiveness criteria relating to process: inclusivity, fairness, resources, transparency, learning, independence and efficiency (Chilvers, 2008; see Figure 7.1). Whilst there is much agreement that these criteria are pertinent for participatory appraisal practice in general, as a distinct and evolving subset of this field analytic-deliberative processes such as DM require further attention.

N1. *Inclusivity*: the process should be representative of all those interested and affected by a decision or action and remove unnecessary barriers to participation.

N2. *Fairness*: the process should allow all those involved to enter the discourse and put forward their views in interactive deliberation that develops mutual understanding between participants.

N3. *Resources*: the process should provide sufficient resources (information, expertise, time) for effective participation.

N4. *Transparency*: the process should be transparent to all those inside and outside of the process about objectives, boundaries, and how participation relates to decision making.

N5. *Learning*: the process should enhance social learning of all those involved, including citizens, specialists, decision makers and wider institutions.

N6. *Independence*: the process should be conducted (managed and facilitated) in an independent and unbiased way.

N7. *Efficiency*: the process should be cost-effective and timely.

Figure 7.1. Normative (N1 - 7) process evaluation criteria (from Chilvers, 2008).

Building on earlier efforts to develop a framework for the evaluation of analytic-deliberative appraisal processes (e.g. Stern & Fineberg, 1996), an analysis of professional actors' deliberations on effective analytic-deliberative participatory appraisal practice has yielded fourteen grounded principles relating to the process itself, its scientific analysis component, access to information and specialist expertise, and deliberation (Chilvers, 2008). Whilst it is recognised that these principles provide only partial coverage of those broader criteria outlined in Figure 7.1, they offer important insights that guard against the 'technocracy of participation', particularly through their attention to diversity in the provision of information and specialist expertise, and through fostering diversity and difference in deliberations. These principles consider six key evaluation criteria regarding participatory appraisal process: framing, symmetry, supportiveness, diversity, responsiveness and competence (see Figure 7.2).

G1. *Framing*: actively engage citizens and stakeholders as early as possible in the framing stage to define the problem, questions to be addressed, alternative courses of action, and acceptability criteria.

G2. *Symmetry*: actively engage citizens and stakeholders in scientific assessment and evaluation, whilst ensuring a highly interactive, symmetrical, and critical relationship between participants and specialists.

G3. *Supportive*: provide appropriate, meaningful and understandable information that supports deliberation and is transparent by making underlying uncertainties and assumptions explicit.

G4. *Diversity*: provide information and specialist expertise that faithfully represents the range and diversity of views that exist on the issue being considered, whilst emphasising the diversity and difference of different viewpoints, exploring uncertainties, and exposing underlying assumptions during deliberation.

G5. *Responsive*: provide information and scientific assessment that is responsive to the needs, issues and concerns expressed by participants in an iterative way.

G6. *Competence*: ensure that facilitators have adequate substantive understanding of the issues whilst remaining independent and impartial as to the outcomes of the process, whilst allowing enough time for participants to become informed and develop competent understandings.

Figure 7.2. Grounded (G1 - 6) process evaluation criteria (based on Chilvers, 2008).

In addition to the normative and grounded process evaluation criteria outlined above, it is important to reflect on the performance of the participatory appraisals from the perspective of the participants. In line with other recent participatory appraisal evaluations (e.g. Horlick-Jones *et al.*, 2007), evaluation criteria were elicited from participants of the DM process through citizens' written feedback that was requested at the end of the second citizens panel and specialists' audio-recorded and transcribed feedback that was requested at the end of the first and second Multi-Criteria Mapping (MCM) interviews (see Figure 7.3). In addition to a general process 'experience' criterion common to both the citizen and the specialist strands (which was deemed very positive by all participants in both strands), three citizen criteria and five specialist criteria were elicited that can be largely mapped upon the normative and grounded criteria, but accentuate particular issues or angles of interest or concern.

C1. *Resources*: provide sufficient impartial information and time prior to and during the process to consider a range of options.

C2. *Interaction*: provide a diversity of relevant citizen and specialist perspectives and an interactive environment where different opinions are valued.

C3. *Learning*: facilitate the learning of new information and different perspectives that can also support thinking outside of the process.

S1. *Method*: provide an open, systematic and manageable appraisal process that can be bound to the decision context.

S2. *Resources*: provide sufficient time during the process to develop options, criteria, scores and weights, and to interact with citizens.

S3. *Integration*: facilitate coupled quantitative analysis and qualitative deliberation with a diversity of citizen and specialist perspectives.

S4. *Learning*: facilitate verification and reflection on personal and others' perspectives on geoengineering and its alternatives.

S5. *Applications*: provide an elicitation of upstream perspectives that impacts upon decision making and allocation of funding.

Figure 7.3. Citizens' (C1 - 3) and specialists' (S1 - 5) process evaluation criteria.

The normative, grounded and participants' evaluation criteria collectively offer a comprehensive framework for determining the effectiveness and implications of the DM process for future participatory appraisals, which will now be considered in Section 7.1.2. It should be noted here that this evaluation recognises the sometimes instrumental purposes of process evaluations (see Chilvers, 2009). However, the relatively small scale of this DM process is likely to have lessened such politics and sensitivity (see Rowe *et al.*, 2005), whilst every effort has been made to avoid it. It is also important to note that the notion that procedural evaluations such as these lead to better outcomes is not guaranteed (Munton, 2003).

7.1.2 Process performance

In this section the performance and implications of the DM process will be considered in relation to two clusters of effectiveness criteria. First, the propriety of the overall *approach* in Section 7.1.2.1 will draw on five evaluation criteria: fairness (N2); competence (G6); interaction (C2); method (S1); and integration (S3). Second, the provision of *resources* in Section 7.1.2.2 will draw on seven evaluation criteria: resources (N3, C1, S2); transparency (N4); independence (N6); efficiency (N7); and supportive (G3). The remaining evaluation criteria are those that relate to one or more of the four dimensions of responsible innovation: anticipation, reflexivity, inclusivity and responsiveness; and will be considered separately in Section 7.2.

7.1.2.1 Evaluation and implications of the approach

The overall approach was considered both competent and fair, with citizens recounting their experience as part of a 'very well organised' and 'Great cooperative process' where a fully vocal diversity of perspectives 'felt [their] opinions were valued' (anon. Citizens). The selection of additional facilitators for their existing substantive understanding of the issues and their experience in facilitation proved an important element in this respect. Whilst no explicit feedback was offered by citizens on the ease with which they engaged with the approach, one ad-hoc comment described it as having 'too much grey area and room for interpretation', signalling some difficulty in engaging with diversity, complexity and/or uncertainty.

Three specialists considered the approach 'logical' and 'straightforward' and its integration of qualitative and quantitative methods valuable. The following comments were typical:

> 'It's a very logical process, it makes you go through the whole logic of... recognising the linkages between the criteria. Brilliant... Very happy with that' (Specialist I).
>
> 'Focus groups are useful and give good insight. When we couple these with quantitative assessments a holistic approach is quite useful' (Specialist H).

On the other hand, four other specialists found the openness of the method and its resultant complexity difficult to engage with. The spatial scale of the process framing and 'situated' nature of the appraisals was considered particularly difficult by one specialist:

> 'I think it's difficult trying to think globally about these things when we're all embedded in a particular culture, political culture and social culture. Trying to make these judgements on a global scale is hard' (Specialist B).

One implication of this observation would be to involve a greater range of cultural perspectives in future participatory appraisals of this nature. Such enhanced inclusivity would produce a more complete cultural map of the issues under consideration. Of course, specialists' appraisals would remain situated without a more substantial deliberative component that was more symmetrical to the citizen strand. In that way trade-offs with specialist availability could be made in conducting their appraisals in group workshops rather than individual interviews. Indeed, one commented that it would have been:

> '...great to get all those people in a room and start exploring all these points of view... Have a day on it, and argue some of these points out' (Specialist F).

Whilst the well established critique of multi-criteria analyses comparing 'apples and oranges' once emerged, the novelty of this approach in seeking to address this very issue as a transparent heuristic was also recognised:

> 'It's very difficult to put these into... even the same qualitative scale... Because you're comparing apples and oranges' (Specialist B).

> 'But the [approach] is designed to try and compare apples and oranges and as long as it's transparent about that...' (Specialist D).

Whilst it was noted that the approach 'takes account of the uncertainties' (Specialist D), several specialists aired caution on the interpretation of results from the process, and particularly those from the citizens strand. The following comments relating to framing and evidence were typical:

> 'I know that relaying information to the public in a way that is not biased is very challenging... and results are always going to be based on that' (Specialist G).

> 'You do have to apply to some sound logic and sound evidence rather than just what people think because even us experts in the space, our views were based on an hour or two interview. It's based on how I'm feeling at the time, what things my brain could remember,

> my understanding of using this tool, and ultimately the very complex journey of enlightenment that I went on. I would never think my personal view at that time was a totally true reflection of that space' (Specialist H).

The focus on geoengineering was itself considered an important area for cautionary interpretation, where Specialist C conceded that at this point 'Much of it is guesswork'. Notwithstanding the conditional qualifications set by Specialist H above, such uncertainty questions whether the application of 'sound evidence' can be made in a satisfactory manner at present.

7.1.2.2 Evaluation and implications of the resources

Taking place squarely within the upstream phase of geoengineering research and just following the cancellation of the publically controversial Stratospheric Particle Injection for Climate Engineering (SPICE) test-bed, the process was most timely (Cressey, 2012). The sufficiency of time within the DM process was a key resource issue for participants, even as they recognised constraints on both the research timetable and on their own time. Citizens and specialists alike remarked that they would have liked to have had more time to consider the options and issues in more depth. Despite this, the citizens in particular proved through their capable engagement to have been given sufficient time to become informed and develop competent understandings of the complex issues; with the possible exception of understanding the new market mechanism option in the women's group. The following comments were typical:

> 'If we had more time I would have liked to go into further detail with the criteria' (anon. Citizen).

> 'One would probably want to spend hours thinking about it... I'd probably spend a couple of days thinking about it. And then I'd see the final results and go back to the beginning. Probably one would reiterate it' (Specialist L).

The information provided in the process, including the initial range of options under consideration, was considered appropriate by the specialists who were also encouraged to identify and appraise additional options they felt were missing from the core and discretionary options. By contrast, a number of citizens remarked that they would have liked to have had a broader range of options to consider, along with more detailed information. This broader range consisted solely of renewable energy options, including geothermal, hydroelectric, solar, and wave sources as well as forms of home electricity generation. Trade-offs with scaling up process complexity, time and budget would be required to realise such a significant expansion of options in future appraisals.

> '[The] process only considered a limited number of options' (anon. Citizen).

> '[It] would have been useful to have more information on some options' (anon. Citizen).

Information on the objectives and boundaries of the process were explained fully and transparently to all participants from the onset, as was its relationship to decision making via a planned governmental policy briefing. The information and facilitation was designed to be unbiased and this was reflected in the citizens' feedback on process independence: '[I] liked having impartial information and opinions available' (anon. Citizen).

The provision of expert and stakeholder specialist expertise through the participation of Specialists E and F in the joint workshop was considered helpful by the citizens. On the other hand, the specialists themselves cautioned as to the diversity of opinion that they represented:

> 'I think you might have picked two very similarly positioned experts... If you wanted a more diverse range of experts [Specialist F] and I were probably not the right choice. In hindsight, if you wanted a nice chat over a cup of tea, pro-science NGO... and sensible chaps like [Specialist F] and me you end up with a less strong diversity of opinions' (Specialist E).

Of course, the unavailability of the other specialists for the joint workshop made this diversity difficult to attain. Alternative means of citizen-specialist interaction were offered to those others in the form of digital media through live video uplink, recorded video, or written statements, none of which were adopted. In further support of scaling up the process in future appraisals, the inclusion of additional specialists and more incentives for wider specialist participation would likely increase the diversity of expert views present.

Scaling up the DM process would of course increase the budgetary requirements of any future appraisals. The process was, as it stood, highly cost-effective, exacting costs of ~£40,000 including researcher time, resources and supervision. Whilst the process had been significantly scaled down compared with other DM processes, this still represents a substantial proportional reduction from an estimated cost of just over £200,000 (see Davies *et al.*, 2003).

7.2 Supporting Responsible Innovation

In Chapter 2 it was established that appraisals of geoengineering should form a part of broader ambitions to realise frameworks for responsible innovation. Subsequent to the preceding internal evaluation, this chapter now turns to an external evaluation of the DM process in order to determine its contributions to the four key dimensions of responsible innovation: anticipation, reflexivity, inclusion and responsiveness (Owen *et al.*, 2013; Stilgoe *et al.*, 2013). These contributions are discussed in relation to their implications for broader systems of governance.

This evaluation will be considered with respect to four clusters comprising the remaining evaluation criteria from Section 7.1. These clusters are structured around the four dimensions of responsible innovation and will be considered in three sections. First, the contributions made in describing and analysing the possible impacts of geoengineering will be examined in Section 7.2.1 (anticipation). Whilst this section does not explicitly draw on the evaluation criteria *per se*, instead it synthesises and exemplifies some of the significant anticipations made in Chapters 5 and 6. Second, the contributions made in reflecting on the different framings and uncertainties that underpin such assessments will be examined in Section 7.2.2 (reflexivity). Four evaluation criteria will be drawn upon: learning (N5, C3, S4); and framing (G1). Third, the contributions made in opening up geoengineering appraisal to diverse perspectives, and ultimately in developing the capacity for systems of governance to respond to those perspectives as they change with evolving circumstances, will be examined in Section 7.2.3 (inclusivity and responsiveness). Six evaluation criteria will be drawn upon: inclusivity (N1), symmetry (G2), diversity (G4); responsive (G5); and applications (S5) (see Tables 7.1, 7.2, 7.3).

7.2.1 Anticipating the impacts of geoengineering

Recent controversies relating to geoengineering experiments such as the UK's SPICE project (Macnaghten & Owen, 2011), the LOHAFEX (Iron Fertilisation Experiment) trial (Strong *et al.*, 2009) and the 'rogue' iron fertilisation of the Haida Salmon Restoration Corporation (Tollefson, 2012) stress the importance of the sort of anticipatory appraisal conducted in this thesis. The capacity for governance to anticipate possible intended and unintended impacts of geoengineering is substantively enhanced through the dimension of foresight inherent to the DM process. Table 7.1 exemplifies a number of significant impact anticipations made in relation to the core and discretionary geoengineering options. These impacts, analysed and discussed in detail in Chapters 5 and 6, ultimately contribute to the identification and shaping of desirable and undesirable futures so that resources can be allocated accordingly (te Kulve & Rip, 2011).

Table 7.1. Significant example anticipations pertaining to intended and unintended impact of core and discretionary geoengineering options.

Geoengineering proposal	Intended impacts	Unintended impacts
Biochar	Land-use limits to scale of impact	Changes to soil quality
Air capture and storage	Limits to CO_2 reservoir storage	CO_2 reservoir destabilisation
Stratospheric aerosol injection	Difficult optimal particle size†	Termination effect rapid warming†
Iron fertilisation	Unreliable sequestration mechanic	Marine ecosystem transformation
Cloud albedo enhancement	Regional limits to scale of impact†	Inadvertent warming from CCN
Space reflectors	Does not help ocean acidification†	Regional weather pattern change†

Acronym: cloud condensation nuclei (CCN). † indicates impacts that apply to other solar geoengineering proposals, with the exception of engineering optimal particle size for space reflectors. The example intended and unintended impacts included in this table are necessarily selective and do not show the full range of impacts elicited against the two criteria groups from which they are drawn (efficacy and environment), nor do they show the impacts elicited against the other criteria groups. Refer to Chapters 5 and 6 for a comprehensive exploration of all identified impacts.

The efficacy criteria group developed during the process offers particular insight into the anticipation of the intended impacts of geoengineering proposals. First, the group exposes the different possible instrumental purposes of the proposals, be they to either: reduce global temperature; reduce the atmospheric concentration of CO_2 or other greenhouse gases; reduce the impacts of climate change; or accomplish any of the former purposes on their own terms or within a desired climatic response time. Second, the group anticipates the possible difficulties in achieving those efficacies. Table 7.1 exemplifies some of the most significant of these difficulties across the proposals, spanning possible spatial limits, engineering challenges, capricious systems, and completeness.

Several of the criteria groups developed in the DM process sought to anticipate the possible unintended impacts of geoengineering proposals, identifying side effects that may cause: environmental repair or damage; economic benefit or cost; safety assurance or concerns; political harmony or discord; social justice or injustice; ethical consensus or dispute; and co-benefits or co-problems. Table 7.1 exemplifies some of the most significant of these difficulties across one such group of criteria: environmental. These span possible harmful systemic transformations, instabilities, (in)controllability, or even the prospect of exacerbating the existing risks of climate change.

Such anticipations pose implications for both decision makers and the scientific community. The different instrumental purposes of geoengineering invites reflection on what is ultimately trying to be achieved through geoengineering. If, for example, the objective is to 'achieve... stabilisation of greenhouse gas concentrations in the atmosphere' as outlined in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) (1992); then solar geoengineering proposals, which unlike their carbon geoengineering counterparts do not remove the greenhouse gases from the atmosphere, cannot directly contribute to that end. The manifold foreseen difficulties in attaining those intended impacts invites reflection on where, or whether, resources can be best targeted in resolving such issues.

The possible unintended impacts of geoengineering not only invite researchers and innovators to determine if and how adverse impacts can be alleviated and favourable impacts can be capitalised upon, but also provoke decision makers to consider which of these impacts are acceptable and unacceptable. Of course, even after impacts are characterised and contingencies are planned for, there remains intrinsic uncertainties as well as the risk of completely unforeseen impacts. These impacts, noted most often with reference to stratospheric aerosol injection by participants in the DM process, are by definition beyond the limits of foresight and demand a precautionary approach.

> 'We just don't know, so I'd err on the side of caution saying it's very likely we're going to have problems with this particular system' (Citizen P2)
>
> 'The ones that we can anticipate are going to be the effects on global weather conditions... Nobody knows what's going to happen when we start squirting things into the stratosphere' (Specialist D).

7.2.2 Internal and institutional reflection on geoengineering

The DM process has sought to anticipate the possible impacts of geoengineering, but so too has it invited its participating specialists and citizens to reflect on the different framings and uncertainties that underpin these assessments. It has been reflexive in the way it created spaces for experts, stakeholders and citizens to openly reflect on and learn about their own framing conditions, assumptions, and the social, ethical and political implications of geoengineering technologies in a transparent way. As one specialist participant put it:

> ‘The nice thing about it is that it forces thinking. So it’s forced me to think in all sorts of new ways about things, which is good and bad, because you talk about stuff that you know about, but you also talk about stuff that you don’t know about. But I felt comfortable, because I, in effect, determined the terms for the discussion’ (Specialist D).

This internal reflexivity comprises participants’ reflections on their own and others’ learning and assumptions in appraising geoengineering, as well as on their own identities and places within the issue (see Stirling, 2006). At its most basic level, participants reflected on their learning about the different options available for responding to climate change; and in the case of citizens, about climate change itself and how their learning would influence decisions outside of the process.

> ‘[I] learned more about global warming and the different options available’ (anon. Citizen).

> ‘I’ve thought more about geoengineering... looking at other options is good’ (Specialist K).

In reflecting on their own assumptions in appraising geoengineering proposals, the participants often revealed conditions and caveats under which they assigned their scores of option performance. These included conditions related to how an option might perform under different, but related criteria. For example, the efficacy of different geoengineering proposals was often judged under the assumption that it performed adequately against feasibility criteria.

> ‘Nobody’s demonstrated [air capture and storage] at any kind of scale... But we’re just talking about effectiveness here and assuming we’ve got that scale, yes it’s absolutely fantastic’ (Specialist F).

Caveats of incertitude too played a large role in participants’ reflections, with several contemplating the extent and depth of their own knowledge. Echoing similar reservations raised in other DM processes (see Davies et al., 2003), such reflection largely related to options they were unfamiliar with, but at times related to the criteria they chose to deploy.

> ‘I put a massive range [for stratospheric aerosol injection] because I didn’t know enough to pass judgement. We don’t know how much it’s going to cost or anything like that’ (anon. Citizen).

> ‘This [ethical criterion] is making me into more of a moral philosopher than I actually am. I don’t know my way around this territory very well’ (anon. Specialist).

Some participants also reflected on their own identity and place within the geoengineering issue and more broadly, revealing some of their frames of reference.

> 'I'm not a scientist but hope I can make the world a better place' (anon. Citizen).

> '[Criteria weighting] raises a sort of deep and philosophical question about where do my beliefs come from?' (Specialist B).

> 'My thinking has been very largely conditioned by working on the Royal Society [(2009)] study' (Specialist C).

In reflecting on the assumptions of other participants in the DM process, the specialists commented on both the similarities and differences between their own and others' appraisals. Criteria were one such point of reflection, with Specialist J remarking that 'It's reassuring there's a lot of consistency in the way people go about this'. Option rankings were a key point of reflection, with several participants highlighting points of contrast or disagreement. For example:

> 'It's interesting [anon. Specialist] thinks that [stratospheric aerosol injection] is worse than business as usual, which I'm not sure you can justify' (Specialist E).

Uncertainty too was reflected upon, with those displaying larger ranges being viewed more positively than those with shorter ranges: 'They're pretty uncertain about things, which is fine' (Specialist E), 'Wow... [they are] very certain about things' (Specialist A). Criteria weightings were an important point of reflection, with the exposition of participants' values and priorities. For example:

> 'This [anon. Specialist] is coming out with very positive weightings for SRM. I mean their weights are safety and efficacy. Well, that seems odd to me... The way they've defined efficacy as well is... global temperature reduction... but you're not addressing the suite of problems' (Specialist B).

Specialists reflected on the citizens' engagement in the process positively, whilst one concurrently added some caution as to the role of public engagement in decision making.

> 'The public participation has been excellent, and I think that's been a very useful piece of work' (Specialist F).

> 'It's always fun to talk to the public. You can get some quite wacky views, but that's true of some scientists as well. But as a collective actually they often represent the sensible middle ground... [But] you can get to the point where you allow public engagement to drive things, and you can have the tail wagging the dog a little bit. Because there's all sorts of things that if you allow a few objections push your comfort threshold so high that you don't do an ex-

periment, I think there's a lot of valuable science that just wouldn't have been done in the past, so there is a balance' (Specialist E).

The citizens reflections on others perspectives were confined to those within their group (men's or women's) in real-time, without the instant opportunity to reflect on those of the other group of citizens or those of the specialists' strand. The men's and women's groups engaged with this process quite differently, with the latter group changing their scores in response to others arguments to converge in more of a consensus. This is reflected in the smaller ranges of variability shown in Figure 6.2 in Chapter 6. The men's group, on the other hand, were far less swayed by others' arguments and largely maintained their scores, culminating in greater variability. The specialists too largely maintained their scores following their exposure to the other participants outputs during the second MCM interview.

The concept of reflexivity, however, relates to more than simply internal reflection within and between process participants. The DM process has also made significant advances in the area of more systemic, institutional reflexivity (Pallett & Chilvers, 2013). The interdisciplinary project team itself, composed of two social scientists: the present Doctoral Researcher and Dr. Jason Chilvers, and two natural scientists, Dr. Naomi Vaughan and Professor Tim Lenton, has undergone a process of institutional reflexive learning within the University of East Anglia (UEA). Indeed, having made significant published contributions to the emergent closing down in geoengineering appraisal identified in Chapter 3 (e.g. Lenton & Vaughan, 2009), the latter two team members have shown much reflexive learning through their recognition of that and their subsequent efforts in supporting the opening up agenda pursued by this project. The prospect for further institutional reflexivity lies with those institutions in government, namely the Department for Energy and Climate Change (DECC) for whom the Integrated Assessment of Geoengineering Proposals (IAGP) project (of which this project is part) will report new knowledge and invite reflection on existing positions on geoengineering.

7.2.3 Inclusion and responsiveness in geoengineering governance

Opening up the appraisal of geoengineering to inclusive deliberation was one of the core functions of the DM process, bringing together not only a diversity of specialists but also of stakeholders and citizens. These different groups were purposefully sampled for a diversity of perspectives (outlined in Chapter 4) with inclusion at the centre of ambitions for normative democratic deliberation and for substantive co-produced governance of innovation (Sykes & Macnaghten, 2013). In turn these perspectives developed a diversity of options and their alternatives, criteria and their weightings, and scores of performance and their overall rankings, each of which are analysed and discussed in detail in Chapters 5 and 6. Taken together they offer insight to the different framings adopted by different perspectives and help to identify issues of possible contestation (Owen *et al.*, 2013).

The citizen participants in particular recognised the inclusion of different perspectives within the DM process, noting both its diversity and its relevance: '[It was] good to hear so many diverse opinions' (anon. Citizen); '[An] interesting and relevant mix of people' (anon. Citizen). Nevertheless, one participant remarked on the statistical representativeness of the process: '[You] need a much bigger sample' (anon. Citizen). Of course, the DM process does not seek such representation but rather the mapped representation of diverse perspectives. This does not mean that more perspectives would not be welcome, however. On the contrary, in Sections 7.1.2.1 and 7.1.2.2 the potential for greater cultural diversity and specialist diversity during citizen-specialist interaction was highlighted as priority for further participatory research on geoengineering.

The inclusive deliberation of the DM process has opened up the appraisal of geoengineering to different knowledges and perspectives which in turn bears upon the responsiveness dimension of responsible innovation. This concerns the two meanings of responsiveness in both reacting to and answering stakeholder and public values and perspectives (Pellizzoni, 2004). Responsible innovation demands that responsiveness reacts and answers such perspectives as they change with evolving circumstances (Stilgoe *et al.*, 2013). In this way, the snapshot appraisal of DM process must form part of a broader system of anticipatory governance involving real-time assessment (Guston & Sarewitz, 2002). In considering such responsiveness within the process itself, it was highly responsive from its conception, allowing participants to frame the issue and set the terms for the appraisal. Furthermore, an additional feature regarding portfolio diversity proposed by the citizen participants themselves, was added in response to their interest (see Chapter 6).

The DM process has also made significant contributions to the broader, systemic idea of responsiveness. Specialist participants in particular were optimistic about the applications of the process, citing the implications of its findings for responsive debate and resource allocation.

> 'I'll be really interested to see what discussions it prompts, because I think that's perhaps its greatest power. The outputs of it are the sorts of things that scientists will be genuinely interested in' (Specialist D).

> 'It should spin out some clearer signals about perceptions and how these things are contextualised in society; and how it might be integrated with their true technological potential and focus of funding' (Specialist H).

One other specialist participant commented on the novelty of its application, and its potential for responding to controversies such as those pervading other emergent technologies:

> 'I don't think this process was undertaken for other large scale controversial science ideas, like GM or nanotechnology; so it will be interesting to see if it makes any difference' (Specialist E).

On the other hand, in considering the opening up properties of the DM process one participant argued that such attention to divergence may in fact complicate decision making aspects of responsiveness

> 'What it doesn't do is the much deeper political and normative challenge of how does showing that [opening up] make the decision any easier? Revealing that actually makes the decision harder' (Specialist B).

Indeed, opening up does pose implications for how appraisals such as the DM process connect with policy and for how institutions respond. Instead of producing the kinds of unitary and prescriptive policy advice that decision makers so often engage with, it yields plural and conditional advice that unveils the depths of uncertainty and diversity of possibilities that exist. The opening up and mapping of divergence inherent to the DM process does not, however, remove the possibility for areas of convergence or consistency (Burgess *et al.*, 2007). Indeed, Chapters 5 and 6 document the remarkable levels of consistency between the two process strands and between their different perspectives. A clear pattern of option performance was found to transcend the different perspectives whilst still documenting considerable diversity.

The potential for anticipatory, reflexive and inclusive appraisal approaches such as the DM process to enhance the responsiveness of geoengineering governance also depends on their connections with wider governance and meta-governance systems of which they are part: 'the governance of governance' (Kooiman & Jentoft, 2009). Such procedural techniques ultimately only form part of a diverse set of ways in which the reflexive and responsive capacities of actors and institutions implicated in governing geoengineering and climate change should be prompted and enhanced in collective-experimental, relational and ongoing ways (Wynne, 1993; Stirling, 2006; Chilvers, 2013; Stilgoe *et al.*, 2013).

7.3 Propositions for Geoengineering Governance

A thematic analysis of the development and deployment of the participants' criteria groups in the DM process, coupled with that of the specialists' foresight exercise conducted at the close of the second MCM interviews, reveals a set of common themes that pervade both the citizen and specialist strands. These themes pose a number of implications for the successful responsible innovation of geoengineering research and development and ultimately its anticipatory governance (Barben *et al.*, 2008). Stylised as four propositions for geoengineering governance in the context of other options for tackling climate change in Figure 7.4, these themes amount to substantive, normative and instrumental conditions under which such research and development should take place.

- Sociotechnical foresight of the futures under which geoengineering proposals and other options for tackling climate change might be considered or deployed and their propriety (condition subsumes all criteria).
- Control of geoengineering technology and other options for tackling climate change through existing political systems and informed acquisition of consent from all interested parties (conditions of political and ethical criteria).
- Anticipation and alleviation of the impacts of geoengineering proposals and other options for tackling climate change on humans and the environment (conditions of environment, safety and social criteria).
- Demonstration of the robustness of geoengineering proposals and other options for tackling climate change under different purposes and innovation pathways (conditions of efficacy, feasibility, economic and co-benefits criteria).

Figure 7.4. Four propositions for the governance of geoengineering proposals and other options for tackling climate change.

These four propositions develop amidst a small but growing literature on geoengineering governance, with which they will be compared and contrasted throughout this section. Unlike other governance principles (Rayner *et al.*, 2013), conditions (Macnaghten & Szerszynski, 2013), or other recommendations for the governance of geoengineering, the present propositions emerge from a process of significant opening up to diverse framings and perspectives. This has in turn yielded a number of novel insights as well as substantial additional contributions to existing governance concepts. This section considers each of these propositions in turn, with a particular focus on geoengineering considerations, unpacking their implications and how such systems could be developed in Sections 7.3.1 - 7.3.4.

7.3.1 Sociotechnical foresight

In Section 7.2.1 the anticipations made by the DM process in exploring the intended impacts of geoengineering proposals were considered. The first proposition for the governance of geoengineering proposals is that such anticipation must extend to the anticipatory and reflexive foresight of their imagined sociotechnical futures (Jasanoff & Kim, 2009). Specialist and citizen participants in the process revealed both implicit and explicit assumptions about these futures during their appraisals through issue framings, criteria development and weighting, and option scoring and ranking. Exploration of these futures subsumes each of the nine criteria groups: efficacy, environment, feasibility, economics, political, safety, social, ethical and co-benefits.

Anticipation and reflection on the sociotechnical imaginaries associated with each of the criteria groups is inextricably linked with the sequential propositions for geoengineering governance. They illustrate different aspects of the imagined futures within which geoengineering proposals might reside. These relate to their possible governance structures (political and ethical criteria), their possible impacts (environment, safety and social criteria), and their possible technical performances (efficacy, feasibility, economics, co-benefits criteria). As such these issues will be addressed through the subsequent Sections (7.3.2 - 7.3.4). However, as the driver of sociotechnical purpose in geoengineering proposals, the efficacy criteria group demands particular attention here.

In considering the efficacy criteria group two central sociotechnical imaginaries emerged. These two imaginaries map directly upon the two dominant problem definitions identified in Chapter 3 as having framed other geoengineering appraisals: the 'insufficient mitigation' frame and the 'climate emergency' frame. What is interesting here is that these frames both emerged independently of each strand and without having been introduced and framed by the research team, suggesting a saliency of these imagined futures around which geoengineering proposals are being driven and constructed. Indeed, it arguably shows the co-production of their natural and social orderings (Jasanoff, 2004).

In considering criteria for greenhouse gas reduction, here the insufficient mitigation frame comes to illustrate a future where additional support, in the form of carbon geoengineering proposals, will be needed in order to realise that intention.

> '[Mitigation] doesn't include anything about removing CO_2 does it?' (Citizen P1).

> '[Carbon geoengineering] could potentially be used to offset some of the harder emissions to abate' (Specialist H).

Such an imaginary is not unorthodox nor is it greatly contested amongst scientists and stakeholders alike, with it increasingly understood that 'dangerous' climate change beyond 2°C cannot be avoided without the deployment of carbon geoengineering proposals (e.g. Anderson & Bows, 2011; McLaren, 2012). Indeed, the technology proposals are now an integral part of two of the new representative concentration pathway (RCP) scenarios used in the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (van Vuuren *et al.*, 2011).

By contrast, in considering criteria for climate change impacts reduction, global temperature reduction, and more overtly for climatic response time, here the climate emergency frame comes to illustrate a future where intentions to reduce greenhouse gases has failed and that solar geoengineering proposals, and particularly stratospheric aerosol injection, are needed to avert disaster.

> 'The only place where [stratospheric aerosol injection] will be acceptable… is when things are looking bleak' (Citizen P2)… 'And once things start to get worse, that argument becomes easier and easier to make' (Citizen P5).

> 'If science tells us we're about to reach a tipping point, then obviously we'll have to start thinking about [solar geoengineering] that ties us over until we've done enough to protect ourselves' (Specialist J).

In common with insufficient mitigation, this imaginary was identified in Chapter 2 as a dominant problem framing. In contrast, however, such an imaginary is unorthodox and greatly contested outside of its small community of proponents (e.g. Blackstock *et al.*, 2009). It is argued that solar geoengineering proposals should be researched in anticipation of and could be deployed preemptively or in response to a defined climate emergency, often illustrated through the idea of climate 'tipping points'. However, such an imagined future rests upon a number of critical substantive and normative assumptions. Pre-emptive deployment would require the reliable 'early warning' of such an emergency, for which the possibility for prediction is viewed as limited due to noise (e.g. Ditlevsen & Johnsen, 2010; cf. Lenton, 2011). Correspondingly, responsive deployment would require the reliable identification of such an emergency once an Earth system had 'tipped'. Perhaps the most critical assumption in both of these cases is that the normative notion of an emergency can be collectively defined and agreed, and that solar geoengineering action in advance of or in response to such a definition can be agreed.

In this critical upstream phase of science and technology in which geoengineering resides it is important that these sociotechnical imaginaries, opened up to alternatives, are fully anticipated and reflected upon both internally and institutionally, inclusively with diverse experts, stakeholder and citizens. The DM process has begun to map these issues, but must form part of an ongoing real-time technology assessment (Guston & Sarewitz, 2002). The implications of this are for decision makers to reflect on the desirability of these futures and the possible contestations that might arise from efforts to delineate them. However, Specialist D stressed that caution should be taken in pursuing such foresight, arguing that mere talk of the future of geoengineering risked the reification of the technology proposals before their physical existence is realised. They argued that such reification might prematurely move the debate towards questions of whether an option should be deployed or not deployed, bypassing critical anticipatory conversations about uncertainty and opportunity. The SPICE project was referred to as a case in point, and a missed opportunity for seeing 'what good research looked like'.

7.3.2 Technology control and consent

The second proposition for the governance of geoengineering is that the technology proposals should be controlled through existing political systems with the informed acquisition of consent from all interested parties. This proposition speaks directly to the Collingridge 'technology control dilemma' (1980, 1982) and the fifth and second principles of the Oxford Principles respectively, where the governance of geoengineering should be emplaced before deployment and public participation should contribute to decision making (Rayner *et al.*, 2013). It also builds upon the fourth and fifth conditions for the public acceptance of [solar] geoengineering outlined by Macnaghten & Szerszynski (2013), where governance should be effective in its political organisation and accommodated within existing democratic systems. Aspirations for this technology control and informed acquisition of consent concern two criteria groups: political and ethical.

In considering political criteria, geoengineering proposals must be politically viable and acceptable, with governance in place before deployment and cooperation between national or international institutions as appropriate. In terms of ethical criteria, geoengineering proposals should espouse intragenerational and intergenerational fairness in both their availability and impacts under appropriate mechanisms for ownership and control, and be controlled for potential misuse. The issue of consent was a theme of particular focus in considering ethical criteria with both citizens and specialists, raising different questions about the proposals that echoed the sentiments of Humphreys (2011). With notable exceptions that operate in the global commons (e.g. iron fertilisation, ocean-based enhanced weathering), carbon geoengineering proposals were viewed as less problematic with local implications for consent:

> 'Who will agree where [biochar, air capture and storage, stratospheric aerosol injection and afforestation] go? Everyone will be NIMBY, and you know the small little poorer areas will get bullied into having an air capture unit stuck in a field' (Citizen P3).

> '[Air capture and storage:] It's a technology that doesn't.... necessarily require a lot of multilateral agreement. An individual nation or entrepreneur could decide to go ahead with it. I suppose there's some political issues around siting and storage, which we know are quite significant' (Specialist B).

In contrast, but similarly with notable exceptions that operate within the territorial sovereignty of states (e.g. urban or crop albedo enhancement), solar geoengineering proposals were viewed as more problematic and posing global implications for consent.

> 'Is it morally fair to impose a solution like [stratospheric aerosol injection] on people that might not know it's happening?' (Citizen P12).

> 'I don't envisage a set of circumstances in which you could ever get something that looked like consent, either informed and given, or assumed, in anything like a satisfying way' (Specialist D).

The Royal Society (2009, p51) stated that 'Geoengineering methods should... only [be] deployed by common consent' but did not engage with what form such consent should take nor how it might be obtained. Consent for those proposals that operate within territories may be acquired through existing consultation procedures such as through the UK's development consent process as part of the Planning Act 2008, but as citizen participant P3 noted, even these can be contested through so-called NIMBYism (Gipe, 1995). Nation-level consent for those proposals that operate within the global commons may be acquired through seeking United Nations consensus or weighted voting (Humphreys, 2011), but these systems are open to veto and contestation with regards the allocation of voting shares. This issue of informed consent raises particular issues for those commons-based proposals with truly global implications, such as stratospheric aerosol injection.

In addition to the appraisal criteria, the specialists' foresight exercise explicitly sought to address participants' views on the governance implications of different geoengineering proposals, most of which concerned this proposition of technology control and consent. Four broad issues emerged concerning (1) the situated governance of proposals in context with mitigation alternatives; (2) governance of proposals on a case-by-case basis; (3) control of geoengineering experimentation; and (4) control of unilateral geoengineering action and multilateral agreement.

There was strong agreement amongst participants that mitigation options should always be given priority over geoengineering proposals, which were viewed by Specialist C as an insurance policy. Whilst the imagined futures of insufficient mitigation and climatic emergency outlined in Section 7.3.1 around which carbon and solar geoengineering proposals were envisaged respectively, the proposals were considered to bear very little in common with one another and that the carbon-solar dichotomy, as well as the even more aggregated umbrella term 'geoengineering' was unhelpful. Such findings resonate with recent calls to disaggregate the term (Heyward, 2013; Boucher *et al.*, 2013).

It was noted by all participants that no single regulatory framework would effectively govern the disparate suite of proposals that had been forced under the 'geoengineering' umbrella. Indeed, disaggregating the governance needs of the different proposals was described by Specialist D as '...going to be messy and complicated with a lot of twists and turns'. Specialist B affirmed that the proposals would need to be governed on a case by case basis, remarking 'I can't offer a nice, neat set of principles'. It was noted that in many cases, established geoengineering proposals such as afforestation could be covered by existing governance structures. Specialist C suggested that other existing governance structures could be modified and extended to cover other proposals, such as is the case with iron fertilisation and the London Convention (IMO, 2007; 2013). Such broadly optimistic views resonate with Humphrey's (2011) whilst contrasting with the more cautious Virgoe (2009). On the other hand, more difficult and novel governance issues were noted to arise from solar geoengineering proposals, in particular stratospheric aerosol injection (see also Macnaghten & Szerszynski, 2013). Transboundary effects and geopolitical relations were seen to be key points of contestation. Existing geoengineering governance projects such as the SRMGI

(SRMGI, 2011) and the Oxford Principles (Rayner *et al.*, 2013) were said to be 'pushing in the right direction' (Specialist D).

Specialists E and I both expressed their beliefs that geoengineering field trials would be likely in coming years. Both referenced the recent and controversial iron fertilisation experiments conducted by Canadian scientist Russ George (Lukacs, 2012), suggesting that trials of stratospheric aerosol injection would soon follow. Indeed, participant I even suggested that such trials could take place in the US by the mid 2020's, perhaps in response to extreme weather events, with other nations likely to follow suit. Whilst Specialist I remarked that effective governance arrangements were unlikely to be ready in time for such trials, Specialist E suggested that there would be swift moves to resist them. Specialist L communicated the essential need for geoengineering governance structures to be in place before full-scale deployment was considered, and preferable need even before small-scale field trials. These comments echo the call for 'governance before deployment' in the Oxford Principles (Rayner *et al.*, 2013).

A dichotomy of governance implications emerged around those geoengineering proposals that would operate locally within nation states and those that would operate globally and internationally. The former group of proposals were considered to be largely unproblematic, falling under the jurisdiction of territorial governance regimes. The latter group of proposals, however, were viewed as requiring multilateral agreement sought through a global institution, most likely the United Nations (UN), echoing research by Virgoe (2009) and recent calls for decision making on geoengineering to be made within the United Nations Framework Convention on Climate Change (UNFCCC) (Zürn & Schäfer, 2013). Several participants noted the irony of this pursuit, with participant L remarking: 'it could take as long as the climate negotiations themselves'. Negotiating the terms of such an agreement, such as what temperature to set the 'global thermostat' were seen as intractable issues. Whilst participants noted that multilateral agreement should be sought for those geoengineering proposals with global, international implications, the risk of unilateral or consortia-led deployment remained. Stratospheric aerosol injection was of particular concern in this regard: 'We keep moving very quickly towards the SRM [Solar Radiation Management] conversation, because that's where the danger is' (Specialist F). The geopolitical tensions that could arise from such an endeavour were considered a matter of acute concern.

7.3.3 Anticipation and alleviation

The third proposition for the governance of geoengineering proposals is that their potential impacts on humans and the environment should be both anticipated and alleviated. The term 'anticipate' is used here in the same way as one of the four dimensions of responsible innovation of the same name, meaning the description and analysis of potential impacts brought about by geoengineering, and particularly those that are unintended (Owen *et al.*, 2013). The term 'alleviate' is used here to mean the deployment of measures to prevent or counteract such impacts, together with their ongoing monitoring. This second proposition draws upon three of the criteria groups developed by the citizens and specialists in the DM process: environment, safety and social.

The proposition stipulates that geoengineering proposals should be subject to the anticipation and alleviation of these impacts within and between these key criteria groups, espousing the dimensions of anticipation and reflexivity in responsible innovation. Environmental impacts and side effects should be minimised during research and development (including carbon footprint) and deployment, including those that are transboundary; whilst impacts should also be reversible. Impacts and side effects on humans (including socioeconomic impacts) should also be minimised, whilst the proposals should be socially and culturally acceptable as part of safety and social criteria.

The anticipation and reflexivity dimensions of responsible innovation that are fundamental in the anticipation and alleviation of geoengineering proposals' possible impacts must be coupled with the dimension of responsiveness if such experimentation is to be responsibly governed. A host of techniques and approaches for building responsiveness are available for this purpose. These include conventional regulatory approaches and standards, such as are under review in the case of iron fertilisation (IMO, 2007). In more extreme cases, experimentation may be subject to the precautionary principle or suspended altogether through moratoria, such as has been employed by the United Nations Convention on Biological Diversity with respect to iron fertilisation experimentation initially, and later geoengineering more widely that 'may affect biodiversity' (UN CBD, 2010). Value-sensitive design also offers the potential for embedding (certain) ethical values in innovation (Friedman, 1996).

Stage-gating (Cooper, 1990) is another such method that can be used to build responsive governance choices, and has already been successfully implemented within the context of geoengineering (Macnaghten & Owen, 2011; Stilgoe *et al.*, 2013). In dividing research and development into distinct stages the mechanism allows for the core dimensions of responsible innovation: anticipation, reflection, inclusion, and ultimately responsiveness; to bear upon decisions to allow or deny progression towards deployment at critical intervals. Indeed, the aforementioned geoengineering case study (the test-bed for a delivery mechanism for stratospheric aerosol injection as part of the SPICE project) was postponed in part because of a failure to satisfy particular stage-gate criteria relating to communications, impacts, and stakeholder and public engagement.

Table 7.2 exemplifies a range of possible significant stage-gate criteria for each of the core and discretionary geoengineering options under scrutiny concerning the anticipation and alleviation of their safety and social impacts.

Table 7.2. Significant stage-gate criteria regarding the anticipation and alleviation of core and discretionary geoengineering options' safety and social impacts.

Geoengineering proposal	Stage-gate criteria
Biochar	Risks of land-use conflicts managed and deemed acceptable
Air capture and storage	Risks of reservoir destabilisation managed and deemed acceptable
Stratospheric aerosol injection	Risks of impact distribution identified and deemed acceptable†
Iron fertilisation	Risks to marine ecosystems managed and deemed acceptable
Cloud albedo enhancement	Risk of inadvertent warming managed and deemed acceptable†
Space reflectors	Risks of changes in weather patterns identified and deemed acceptable†

These illustrative stage-gate criteria draw on significant safety and social issues cited within the DM process. The unintended impact anticipations in Table 7.1 also illustrate significant environmental stage-gate criteria. † indicates impacts that apply to other solar geoengineering proposals, with the exception of inadvertent warming for stratospheric aerosol injection and space reflectors.

7.3.4 Demonstration of robustness

The fourth proposition for the governance of geoengineering proposals is that they should be demonstrably robust under different purposes and innovation pathways. The term 'demonstration' is used here broadly to mean the extent to which a proposal has been tested and shown to adequately function, ranging from basic theoretical research to computational modelling to laboratory development to subscale field testing (and so on) (cf. Blackstock, 2010). The term 'robustness' is used here as an essential factor for evaluating alternative policy decisions under states of uncertainty (Rosenhead *et al.*, 1972; Lempert *et al.*, 2006), much in the same way as robustness has been proposed to hedge against possible option vulnerabilities to different plausible future narratives (operationalised through criteria) in climate change adaptation policy (see Dessai *et al.*, 2011). This first proposition draws upon four of the more technical criteria groups developed by the citizens and specialists in the DM process: efficacy, feasibility, economics, and co-benefits.

The proposition stipulates that geoengineering proposals should be subject to the demonstration of robustness within and between these key criteria groups, espousing the dimensions of anticipation and reflexivity in responsible innovation. In terms of efficacy, geoengineering proposals must demonstrate the significance of their potential to: reduce global temperature; reduce the atmospheric concentration of greenhouse gases; reduce the impacts of climate change; and realise those potentials on their own terms; within a particular climatic response time; and for a particular duration of effect. In terms of feasibility, the proposals must demonstrate their technological maturity with respect to their: technical understanding and viability; access to required resources; and expected development time. In terms of economics, the proposals must demonstrate the viability of their: commercial market potential; public investment needs; return on investment; cost-benefit ratio; cost-effectiveness; and sustainability over time. In terms of co-benefits, the proposals must demonstrate their capacity to produce benefits that are additional to their primary purpose.

As defined above, the 'demonstration' of geoengineering proposals requires some level of testing or experimentation and proof of adequate functioning. Indeed, 'experimentation' was a central theme in the specialists' foresight exercise regarding the future of geoengineering and runs as a central theme throughout the four propositions. Two participants in particular drew upon recent experiments, including the 'rogue' iron fertilisation by the Haida Salmon Restoration Corporation (Tollefson, 2012), and suggested that more field trials were likely to occur in the near future:

> 'There will be the odd outdoor experiment in the next few years, by people who shouldn't be doing them; like Russ George' (Specialist E).

> 'You will see experimentation in the US with stratospheric aerosols; you will see pressure building within the political community in the US to try it out. I predict that between the mid-twenties and mid-thirties it will be deployed in the US and I wouldn't be surprised if some other nations follow suit' (Specialist I).

Much as with the anticipation and alleviation of geoengineering proposals' possible impacts the responsive stage-gating approach can be used to control such experimentation. Table 7.3 exemplifies a range of possible stage-gate criteria for each of the core and discretionary geoengineering options under scrutiny concerning their robust demonstration of feasibility and economics. Even now the different proposals are understood to pose different issues and at different levels of technological maturity. Feasibility stage-gate criteria range from determining the scale up viability of the proposals to the fundamental viability of the proposals in principle. Economic stage-gate criteria range from determining the market viability of the proposals to the fundamental viability of cost.

Table 7.3. Illustrative significant stage-gate criteria regarding the robust demonstration of core and discretionary geoengineering options' feasibility and economics.

Geoengineering proposal	Stage-gate criteria
Biochar	Scalability and market potential deemed viable
Air capture and storage	Scalability and cost/tonne CO_2 sequestration deemed viable
Stratospheric aerosol injection	Optimal particle size attained and full base-cost deemed acceptable
Iron fertilisation	Sequestration deemed effective, cost-benefit ratio deemed acceptable
Cloud albedo enhancement	Optimal particle size attained and development costs deemed viable
Space reflectors	Manufacturing costs and orbital transport costs deemed viable

These illustrative stage-gate criteria draw on significant feasibility and economic issues cited within the DM process. The intended impact anticipations in Table 7.1 also illustrate significant efficacy stage-gate criteria. Significant co-benefits criteria would demand 'Sufficient co-benefits identified' for each of the geoengineering proposals under consideration.

Conclusions

This chapter has presented a synthesis discussion of the DM process' implications for the governance of geoengineering proposals. It began by evaluating the performance and implications of the process approach and resources, showing different participants experiences in engaging with DM. Whilst participants generally felt that more time and more resources would have been beneficial, they recognised commitment constraints of their own as well as the researchers. In the specialists reflections, all of the specialists and stakeholders remarked at the heuristic utility of the approach in mapping the extensive scope of issues raised by geoengineering. Indeed, the resultant complexity was considered 'difficult' to engage with by some but 'logical' and 'straightforward' for others. The systematic rigour of the process, its flexibility to different participants' engagements and its openness to diverse framings and perspectives were all cited as strengths.

The contributions that DM has and can make to supporting responsible innovation have also been explored, showing its anticipatory, reflexive, inclusive and responsive values. Recent controversies relating to geoengineering experiments have been shown to stress the importance of the sort of anticipatory appraisal conducted in this thesis. The aptitude for governance to anticipate possible intended and unintended impacts of geoengineering has been substantively enhanced through the DM process capacity for foresight. The process has also invited its participating specialists and citizens to reflect on their assessments, creating spaces for them to openly reflect on and learn about their own framing conditions, assumptions, and the social, ethical and political implications of geoengineering technologies in a transparent way. Moreover, as part of a wider research project, the IAGP, and institution, the UEA, it has built wider institutional reflexivity and has hopes to impact further in national government. It has opened up the appraisal of geoengineering to inclusive deliberation, bringing together not only a diversity of specialists but also of stakeholders and citizens. Although dependent on its connections with wider governance and meta-governance systems, through its these anticipatory, reflexive and inclusive dimensions the DM process enhances governance responsiveness.

Finally, through a thematic analysis of the development and deployment of the participants' criteria groups in the DM process, coupled with that of the specialists' foresight exercise conducted at the close of the second MCM interviews, this chapter has yielded four successive propositions for geoengineering governance in context with other options for tackling climate change. The first of these propositions argues that governance should seek to build sociotechnical foresight of the future circumstances under which geoengineering might be considered or deployed. The second of these propositions argues that control of geoengineering technology should be sought through existing political systems, guarding against the technology control dilemma through anticipatory forms of governance. It also stipulates that public consent should be sought from all interested parties in order for geoengineering to lay claim to any legitimacy. The third of these propositions argues that the possible impacts of geoengineering should be anticipated and avoided, or alleviated where possible. The fourth and final proposition argues that a responsible demonstration of geoengineering technology robustness should take place under different purposes and innovation pathways.

The next and final chapter draws together the overall conclusions of the thesis and relates them to the initial research questions outlined in Chapter 1.

Chapter 8

Conclusions

This concluding chapter addresses the research themes and questions set out in the first chapter and presents conclusions and key insights from across the thesis. The chapter begins by addressing those research questions relating to the framing of geoengineering appraisal in Section 8.1, both within current appraisals and within the Deliberative Mapping (DM) process presented in this thesis (relates to Chapters 2, 3, 5 and 6). Those research questions relating to the appraisal of geoengineering by specialists and citizens are then addressed together in Section 8.2, reflecting on the substantive performance of different geoengineering proposals and of their alternatives, and on the implications of these findings for policies on tackling climate change (relates to Chapters 5 and 6). Those research questions concerning the governance of geoengineering are then addressed in Section 8.3, reflecting on the propositions for governance and the implications for policy in practice (relates to Chapter 7). The thesis then concludes by discussing its limitations in the context of challenges and questions for future research in Section 8.4, and by summarising its substantive contributions to the academic and policy literatures in a final conclusion.

8.1 Framing Geoengineering

In this section research questions relating to the framing of geoengineering appraisal within current appraisals and within the DM process are drawn from the first, second and third research themes, and will be addressed in turn. The first research theme, 'framing geoengineering appraisal' posed two research questions relating to the framing of current appraisals:

- Research Theme 1: Framing Geoengineering Appraisal
  1. How important are framings in current appraisals of geoengineering and what effect do they have on their capacities to 'broaden out' inputs and 'open up' outputs?

2. What would constitute a suitable methodological response in appraisal design to the limitations of current appraisals of geoengineering?

In response to these research questions the first critical analysis of current geoengineering appraisals was undertaken in Chapter 3. The role of framings in shaping appraisal inputs and outputs was explored in three key parameters: (1) the definition of the problem or issue in question and the contextual situation of geoengineering proposals; (2) the methods and criteria selected to conduct these appraisals; and (3) the level of reflexivity with which appraisal outputs were conveyed and the overall recommendations of geoengineering appraisals.

Current appraisals of geoengineering were found to have chiefly framed the problem definition as one of 'insufficient mitigation' or a 'climate emergency'. This has placed geoengineering proposals in 'contextual isolation' of their legitimate alternatives spanning mitigation and adaptation by including only options capable of addressing these narrowly-framed definitions. In light of the review of contemporary theoretical perspectives on social appraisal undertaken in Chapter 2, it is clear that a suitable methodological response to this limitation should be inclusive of these alternatives by broadening out the problem definition.

Current appraisals of geoengineering were also found to have employed methods that are primarily expert-analytic and reductive-aggregative in their nature. This does not adequately respond to the post-normal scientific context in which climate change and geoengineering resides by excluding broader stakeholder and public participation. Concurrently it does not adequately respond to the indeterminate uncertainties and incertitude that pervades the issue. Moreover, the criteria employed by such methods are mostly technical, marginalising vital and broader political, social and ethical issues amongst others. A suitable response in appraisal design should employ an inclusive, participatory, and integrated analytic-deliberative appraisal methodology that recognises the indeterminate uncertainties and incertitude that bears upon the issue and introduces a diversity perspectives and criteria from stakeholders and publics as well as experts through a broadening out of its inputs.

Current appraisals of geoengineering were also found to have shown low levels of reflexivity in recognising their different framings. Appraisals of geoengineering have thus begun to 'close down' upon particular geoengineering proposals, principally stratospheric aerosol injection, though narrow and closed framings that often culminate in unitary and prescriptive decision recommendations. A suitable methodological response should instead seek to reflexively 'open up' with respect to its framings and yield plural and conditional decision recommendations that do justice to the myriad complexities and uncertainties that pervade climate change and geoengineering and thereby avoid risks of path dependency and premature 'lock-in'.

In responding to each of these limitations of current appraisals of geoengineering, the innovative DM was identified as the most suitable methodological response in appraisal design; for its opening up approach (Stirling, 2008) and its particular attention to wider and diverse stakeholder and public participation 'upstream' of significant research and development or public controversy (Wilsdon & Willis, 2004; Rogers-Hayden & Pidgeon, 2007); analytic-deliberative integration (Stern & Fineberg, 1996); indeterminate ambiguity and ignorance in uncertainties and incertitude (Wynne, 1992a; Stirling *et al.*, 2007); and anticipatory, reflexive, inclusive and responsive dimensions in developing a framework for responsible innovation (Owen *et al*;. 2013; Stilgoe *et al.*, 2013).

The second and third research themes, 'specialist and public appraisal of geoengineering' posed two research questions relating to framings within the DM process:

- Research Theme 2: Specialist Appraisal of Geoengineering
  1. To what extent does diversity amongst experts and stakeholders 'open up' framing of geoengineering appraisal in context with alternative options for tackling climate change?
- Research Theme 3: Public Appraisal of Geoengineering
  1. To what extent does diversity amongst citizens 'open up' framing of geoengineering appraisal in context with alternative options for tackling climate change?

In response to these research questions the DM process was developed and performed and reported in Chapters 5 and 6. The ways in which specialists and experts opened up the framing of geoengineering appraisal can be considered through their unconstrained problem definitions, options, criteria and weightings.

The problem definition for the DM process had been opened up beyond the narrower framings of current appraisals to one of 'responding to climate change'. As part of the citizen strand of the process, however, an additional framing aspect was added. A 'topic blind' framing of 'global environmental issues' on participant recruitment allowed citizens to openly frame climate change and geoengineering prior to the introduction of a 'responding to climate change' framing. Indeed, the citizen participants proceeded to situate the issues within broader, and juxtaposed, problem definitions of human 'overpopulation' and 'resilience' to change. In turn, the problem definition of climate change is characterised by uncertainty in the forms of scepticism and counter-scepticism, and trust in science and its arbiters, and was viewed as a consequence of current economic and political systems. Naturalness, scale and logic were three dominant frames in citizens initial exploration of the options under consideration, the former of which finds resonance with other public participatory research (NERC, 2010; Corner *et al.*, 2013). These broader problem definitions, together with the unconstrained elicitations of DM, have in turn introduced a range of alternative options for responding to climate change by both specialists and citizens. The options spanned renewable, low carbon, local and novel forms of energy, national and international policies, as well as other carbon geoengineering proposals including afforestation, variants of air capture and storage, and enhanced weathering.

Specialists and citizens developed a diversity of 80 unique appraisal criteria that spanned the natural, applied and social sciences. These have been coded into nine overall groups that significantly expand on the range and depth of criteria that have been used in current appraisals: efficacy, environment, feasibility, economics, politics, safety, society, ethics, and co-benefits; where politics and co-benefits were criteria groups developed uniquely by specialists and safety was a criteria group developed uniquely by citizens. Where technical criteria spanning efficacy, feasibility, economics and risk were dominant in current appraisals, political, safety, social, ethical and co-benefit criteria groups have been added. Moreover, in those technical criteria groups, their depth has been expanded. For example, where efficacy has often related to a reduction in global temperature in current appraisals, here it has been opened up to six different criteria sub-groups that have a profound impact on efficacy outcomes in appraisal. Specialists and citizens ranked 'technical' criteria more highly than 'social' criteria, but have shown that important differences exist between the weighted perspectives.

8.2 Appraising Geoengineering

In this section research questions relating to the appraisal of geoengineering in the DM process are drawn from the second and third research themes, and will be taken in turn. These themes, 'specialist and public appraisal of geoengineering' posed two research questions:

- Research Theme 2: Specialist Appraisal of Geoengineering
  2. How do geoengineering proposals perform against alternative options for tackling climate change in specialist appraisals?
- Research Theme 3: Public Appraisal of Geoengineering
  2. How do geoengineering proposals perform against alternative options for tackling climate change in citizen appraisals?

In response to these research questions the DM process was developed and performed and reported in Chapters 5 and 6. In opening up the appraisal of geoengineering to the diverse framings discussed above, a radically different view of option performance has emerged compared with those of current assessments. Geoengineering proposals have performed most often lower than their mitigation counterparts. Within the geoengineering suite of options, carbon geoengineering proposals performed more highly than solar proposals. In particular, where stratospheric aerosol injection has previously outperformed other geoengineering proposals and emerged as an ostensibly effective, feasible and cheap proposal, here has performed very poorly. Its low performance ranking, and those of other geoengineering options, are not only as a result of opening up appraisal criteria to a wider range, including issues of politics, society, ethics and co-benefits, but also a result of opening up appraisal criteria to a greater depth.

A particularly important part of these findings is that they have emerged from within a process that sought to map a divergence of perspectives. Despite this, a remarkable level of consistency has emerged, with the same pattern of geoengineering being outperformed by mitigation options in each specialist sector (with the possible exception of industry specialists), and within each citizen group. These findings suggest to policy makers that resources that could otherwise be invested in mitigation options that perform in a more robust manner across the ensemble of appraisal criteria, are being invested in geoengineering proposals that do not. Of course, this is not to suggest geoengineering research be abandoned or that any can be ruled out at this highly uncertain stage (though of course there are perspectives that would, and have, ruled out certain options on principle). Indeed, many of the proposals outperform the mitigation options under particular criteria. For example, whilst voluntary low carbon living has been appraised highly against environment, economic, political, safety, social, ethical and co-benefits criteria, it has scored very poorly against efficacy and feasibility criteria. Thus it may prove more palatable an option, but not one to sufficiently tackle climate change directly.

It is clear from the findings of this thesis that no one option for tackling climate change is a panacea and policy should reflect the diversity of options and possible pathways at different scales. The analysis illustrates that the term 'geoengineering' comprises a range of disparate technology proposals which have distinct qualities and performance ranges. This could be taken as support for calls to disaggregate the term and for geoengineering proposals to be governed on a case-by-case basis (Heyward, 2013). There is certainly a need to discriminate between different proposals, their innovation contexts, and the imagined futures they invoke. Yet, the approach that has been developed here cautions against moves to consider geoengineering proposals in isolation. Such practice would marginalise vital comparative dimensions and serve to close down the decision context. The key is to open up the framing of appraisals to consider geoengineering proposals in comparative context and avoid premature 'lock-in' to particular options or pathways (Arthur, 1989).

8.3 Governing Geoengineering

In this section research questions relating to the governance of geoengineering are drawn from the fourth research themes, and will be taken in turn. This theme, 'geoengineering governance' posed two research questions:

- Research Theme 4: Geoengineering Governance
  1. What are the implications of 'opening up' geoengineering appraisal for governance?
  2. How might these implications for governance be implemented under a framework for responsible innovation?

In response to these research questions a thematic analysis of the development and deployment of the participants' criteria groups in the DM process was conducted, coupled with that of the specialists' foresight exercise conducted at the close of the second MCM interviews. In doing so it has revealed a set of common themes that pervade both the citizen and specialist strands, culminating in four implications for geoengineering governance that should form part of a wider framework for responsible innovation and anticipatory governance. These themes, stylised as propositions for governing geoengineering in context with other options for tackling climate change, posit first of all that sociotechnical foresight of the future circumstances under which geoengineering might be considered should be explored. The second proposition stipulates that control of geoengineering technology should be sought through anticipatory governance in order to guard against the technology control dilemma (Collingridge, 1980), and that public consent is required to secure legitimacy for any geoengineering action. The third proposition stipulates that anticipation of the possible impacts of geoengineering is important to avoid any undesirable futures, whilst alleviation is important to mitigate those impacts that are likely to occur. The fourth and final proposition stipulates that a demonstration of the robustness of geoengineering technology is needed to responsibly test the theory and practice of the technology proposals before deployment.

8.4 Limitations and Future Research

This thesis has accomplished its stated objective of 'opening up' geoengineering appraisal to a greater diversity of framings than those of current appraisals. It has opened up to broader problem definitions, alternative options, diverse perspectives and criteria; and in doing so revealed a radically different view of option performance, posing important implications for future research and policy. However, as with all research, it is not without its limitations. There is one principal limitation of the research that stems from its modest resources and budget: scale. The research scale was limited to twelve diverse specialists and thirteen citizens who were recruited to participate in two sets of interviews and two citizens panels, respectively, together with a joint citizen-specialist workshop. Whilst this was not intended to be statistically representative of specialists or citizens, but rather to be a rich, exploratory mapping of the issues under consideration; a larger sample size would have inevitably introduced an even greater diversity of perspectives. Of course, under such a modest resource base and budget, numerous project expenses including participant honoraria, venue catering, accommodation and travel claims, quickly escalate with scale.

Perhaps less of a limitation and more of a point for reflection is the framing of the problem definition adopted in this research. In response to the narrower problem definitions of current appraisals of geoengineering that excluded mitigation options and adaptation, such as 'insufficient mitigation' and a 'climate emergency', this research adopted a 'responding to climate change' framing that included these alternatives. Nevertheless, one might argue that this framing is itself too narrow, and that the problem definition should be opened up further, situating geoengineering and climate change within, for example, a 'living with nature' frame. However, broader problem definitions comparable to this were indeed introduced into the DM process by research participants themselves, situating the issues within human 'overpopulation' and 'resilience' frames that see current economic and political systems as the root of the problem.

On the other hand, one might argue that 'responding to climate change' is too broad a problem definition; one that unduly raises the profile of geoengineering proposals alongside mitigation options and adaptation and risks its normalisation or even its legitimisation. As part of the commitment of this research to opening up, however, diverse perspectives that are subsumed under this broader framing compel its consideration. Whilst insufficient mitigation and climate emergency frames are narrow, for instance, they raise legitimate concerns about society's progress towards avoiding 'dangerous' climate change and nonlinearities in the Earth's climate system that are deserving of representation in substantive as well as normative terms. Of course, this does not mean forming a commitment to the proposals, but rather their open social appraisal under diverse perspectives so that decision making on responding to climate change with or without such options can be more transparent, accountable and robust.

This thesis has opened up a range of possibilities for future research that could build upon the findings presented herein and open up geoengineering appraisal in novel ways. It has mapped the substantive performance of different geoengineering proposals, and of different alternative options for tackling climate change. In doing so, it has revealed manifold issues of uncertainty and variability throughout Chapters 5 and 6 that call for further research and policy attention. Often these issues are endemic between the options and span multiple criteria under multiple perspectives. For example, where stratospheric aerosol injection has performed highly with respect to efficacy criteria, it has simultaneously performed poorly under different perspectives. Future research should further explore the nature of these ambiguities in order to determine their salience. As noted in Chapter 6, the notion of option portfolio diversity should also be investigated further to ascertain the role of geoengineering, if any, in option mixes for responding to climate change.

Four propositions for the governance of geoengineering have been shown in Chapter 7 that pose ambitious challenges for their implementation in governance architectures. To support these ambitions, future research should seek to explore these propositions. To build sociotechnical foresight, research should explore the circumstances under which geoengineering proposals might be considered or deployed with a diversity of social actors. Foresight of the circumstances in which solar geoengineering proposals, such as stratospheric aerosol injection, might be considered under a 'climate emergency' scenario could be considered one such research priority. To build control of geoengineering technologies, political frameworks for anticipatory governance should be explored to guard against the technology control dilemma, and explore ethical mechanisms available for determining public consent. To build institutional capacities for the anticipation and alleviation of impacts of geoengineering, future research should further explore what impacts on the environment, society and safety are possible and how such impacts might be avoided or mitigated against. To build demonstrations of geoengineering proposals' robustness, research should seek to test the efficacy, feasibility, economics and co-benefits of different geoengineering proposals in principle and in practice. An essential part of this final proposition is that future research identifies appropriate mechanisms for governing such tests. Each of these propositions should take place under a framework for responsible innovation, espousing anticipation, reflexivity, inclusion and responsiveness.

Continuing to open up geoengineering appraisal during this upstream phase of research and development is essential to guard against premature path dependency and lock-in. In producing plural and conditional policy recommendations, the opening up of geoengineering appraisal that has been pursued in this thesis might appear to make decision and policy making harder than the unitary and prescriptive recommendations of approaches that seek to close down on particular courses of action. However, this need not be the case. Whilst seeking to map a divergence of perspectives, the DM process has concurrently yielded a remarkable degree of consistency in its 'bottom line' results. This consistency exists between diverse perspectives, making those findings especially authoritative and robust.

Other means of opening up geoengineering appraisal should be explored in future research. As was alluded to earlier in this section, this could be pursued through a DM process, or a similarly broad and open process, with a larger budget which would introduce a new level of scale and diversity. In particular, an obvious extension of the DM process would be to include a wider diversity of specialists and citizens. Experts and stakeholders from different disciplines, organisations and with different perspectives on geoengineering could be introduced, as could sociodemographic citizens from other geographical locations around the UK other than Norfolk. An additional element to this further research could be to open this up even further to an international scale, recruiting culturally diverse participants from both developed and developing nations. This is especially important endeavour with respect to those geoengineering proposals with global implications, such as stratospheric aerosol injection. Such diversity would ultimately yield even more diverse problem definitions, options, criteria and weighting perspectives.

Conclusions

This thesis has begun to open up the appraisal of climate geoengineering proposals. It has critically analysed current appraisals of geoengineering and revealed a number of significant and pervasive limitations. Power is exerted through framings in the appraisal designs (Stirling, 2008), situating the proposals in contextual isolation of alternative options for responding to climate change, inadequately responding to the nature of the post-normal scientific context in which geoengineering resides (Funtowicz & Ravetz, 1992; 1993; Wynne, 1992a; Stirling *et al.*, 2007), and ultimately beginning to close down upon particular proposals. DM was identified as the most suitable response to these limitations, instead seeking to open up option choice, be inclusive of diverse stakeholders and publics as well as experts, and situate geoengineering in context with other options for tackling climate change (Davies *et al.*, 2003; Burgess *et al.*, 2004; Burgess *et al.*, 2007).

In opening up geoengineering appraisal a diversity of alternative framings have emerged spanning perspectives, problem definitions, options, criteria, and weightings. A radically different view of option performance has emerged from these framings, with geoengineering proposals most often being outperformed by alternative mitigation options. In particular, stratospheric aerosol injection, one solar geoengineering proposal that has gained much attention for its ostensibly effective, feasible and cheap performance in narrower assessments, has performed very poorly (c.f. for example, Lenton & Vaughan, 2009; Fox & Chapman, 2011; Royal Society, 2009). By opening up to a greater range and depth of appraisal criteria the proposal, and others, do not perform as well as once thought, under new criteria groups including politics, society, ethics and co-benefits, but also under those existing criteria groups that have been significantly opened up. Remarkably, these findings are consistent between the diverse perspectives that have participated in the DM process. From a process that has sought to map divergence, this unexpected convergence makes these 'bottom line' results more robust.

Four key propositions for the governance of geoengineering have emerged from the DM process that promotes its responsible innovation (Owen *et al.*, 2013; Stilgoe *et al.*, 2013) and anticipatory governance (Barben *et al.*, 2008). Sociotechnical foresight is necessary for anticipating the circumstances under which geoengineering proposals may be considered or deployed (Jasanoff & Kim, 2009). Control of geoengineering technology through a responsive framework for governance is necessary for guarding against the technology control dilemma (Collingridge, 1980), and mechanisms for obtaining consent are necessary for the any geoengineering action to be legitimate. Anticipation and alleviation of the possible impacts of geoengineering are necessary for avoiding or countering their potential risks. A demonstration of geoengineering technology robustness is necessary to prove the proposals' efficacy, feasibility, economics and co-benefits. Future research and policy endeavours should now face decisive challenges in supporting and implementing these ambitious propositions.

Appendices

Appendix 1 Methodology

Appendix 1.1 Appraisal Options

Appendix 1.1.1 Options Review

Option	Strategy				Governance				Instrument			Novelty	
	Geoengineering	Mitigation	Technological	Non-technological	Territorial	Commons	Centralised	Distributed	Regulatory	Market	Voluntary	Novel	Established
AFF	✓			✓	✓			✓	✓		✓		✓
ACS	✓		✓		✓		✓		✓	✓		✓	
BIO	✓		✓		✓			✓		✓	✓		✓
CTX		✓		✓	✓		✓		✓				✓
CAE	✓		✓			✓	✓		✓			✓	
CCS		✓	✓		✓			✓	✓	✓		✓	
C-CSS		✓	✓		✓			✓	✓	✓		✓	
DES	✓		✓		✓		✓		✓			✓	
ENW	✓		✓			✓	✓		✓			✓	
MRG		✓		✓		✓	✓		✓				✓
IRF	✓		✓			✓	✓		✓			✓	
NMM		✓		✓		✓	✓			✓			✓
NFI		✓	✓		✓			✓	✓	✓			✓
NFU		✓	✓		✓			✓	✓	✓		✓	
OSW		✓	✓		✓			✓	✓	✓			✓
URG		✓		✓	✓			✓	✓				✓
URB	✓		✓		✓			✓	✓		✓	✓	
RLC		✓		✓	✓		✓		✓				✓
SPR	✓		✓			✓	✓		✓			✓	
SAI	✓		✓			✓	✓		✓			✓	
VLC		✓		✓	✓			✓			✓		✓

Options highlighted dark grey are those included as 'core' options, and options highlighted light grey are those included as 'discretionary' options. Business as usual was included as an additional core option in order to allow participants to consider 'doing nothing' and contending with the perceived climate change impacts and capacities for adaptation. A range of 'additional' options beyond those included in this review were proposed and appraised by the participants themselves. Acronyms: afforestation (AFF); air capture and storage (ACS); biochar (BIO); carbon tax (CTX); cloud albedo enhancement (CAE); carbon capture and storage (CCS); coal energy with carbon capture and storage (C-CCS); desert albedo enhancement (DES); enhanced weathering (ENW); multilateral regulation (MRG); iron fertilisation (IRF); new market mechanism (NMM); nuclear fission energy (NFI); nuclear fusion energy (NFU); offshore wind energy (OSW); unilateral regulation (URG); urban albedo enhancement (URB); regulatory low carbon living (RLC); space reflectors (SPR); stratospheric aerosol injection (SAI); voluntary low carbon living (VLC).

Appendix 1.1.2 Specialist Options Booklet

Rob Bellamy, July 2012

Dear participant,

Thank you for agreeing to participate. We believe this study is very important and we appreciate your willingness to help us tackle the question: **how should we respond to global warming?** This will involve the multi-criteria appraisal of climate geoengineering proposals relative to climate change mitigation options. In this interview brief we provide a short overview of the process and the definitions of the options to be appraised.

You are one of a number of specialists and stakeholders partaking in a transparent, participatory, multi-criteria option appraisal process called **Deliberative Mapping**. A small group of socially-representative members of the public will also participate in a separate but parallel 'strand' of the appraisal process.

Specialists and stakeholders will independently partake in two face-to-face, **Multi-Criteria Mapping interviews** – the first to conduct your initial appraisal of options for tackling climate change; and the second, to take place some weeks later, to elicit any changes in that initial appraisal in light of appraisal results by other specialists and stakeholders, as well as those completed by the public group.

The Multi-Criteria Mapping interviews will be conducted using a dedicated computer software program called Multi-Criteria Mapper, provided by the researcher. Using this program the researcher will guide you through the multi-criteria option appraisal process, which you will be asked to complete in a *personal capacity*:

1. Identify options for appraisal
2. Elicit criteria by which those options will be appraised
3. Appraise the performance of the options against those criteria
4. Review the outputs

A comprehensive review has established **7 'core' options** for responding to global warming which must be appraised by all participants (see overleaf). There are a further 7 'discretionary' options which you are free to appraise if you wish. You are also free to identify and appraise additional self-defined options, be they option combinations or options not already included.

You will then be asked to develop a common set of **criteria** by which to appraise the options relative to one another. The relative 'best case' and 'worst case' performances of each option under each criterion should then be given a **score** on a scale of 0 – 10, where high scores are always better than low scores. This will produce a visual output of options' performances, where each criterion can then be given a **'weight'** according to their relative importance.

Your Multi-Criteria Mapping interview will produce both quantitative and qualitative outputs: quantitative scores of option performance and a qualitative audio transcript of the reasoning underpinning those scores. These data will be analysed alongside those of the other specialist and stakeholder participants as well as the public participants, producing an overall dataset that seeks to provide a 360° snapshot of the divergent perspectives that bear upon contemporary climate change decision making. You will receive a copy of the project report upon completion.

Thank you once again for your participation, and I look forward to meeting with you. In the meantime if you have any further questions or comments about the interviews or the Deliberative Mapping process as a whole please do not hesitate to contact me.

Kind regards,

Rob Bellamy
Doctoral Researcher

School of Environmental Sciences
University of East Anglia, Norwich Research Park
Norwich, NR4 7TJ
E: r.bellamy@uea.ac.uk
T: (01603) 591346

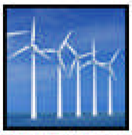
1

'Core' options for tackling global warming – to be appraised by all participants

Option 1 **Voluntary low carbon living**

This energy conservation option is defined by a focus on promoting voluntary reductions in domestic and commercial energy use, in order to mitigate climate change. This could be realised in a number of ways including through the use of social marketing campaigns and the installation of 'smart' energy meters. A number of social marketing campaigns have already occurred (e.g. UK Government 'Act on CO_2') and smart meters are being trialled ahead of a nationwide roll-out.

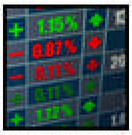
Photo: http://www.momgoesgreen.com/wp-content/light-off.jpg



Option 2 **Offshore wind energy**

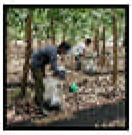
This low carbon energy option is defined by a focus on increasing the proportion of the world's energy that is provided by offshore wind electricity, in order to mitigate climate change. This could be realised by increasing the removal of barriers to delivery (e.g. in the planning system) and through increasing direct investment (e.g. in the Renewables Obligation). Offshore wind turbines currently represent approximately 1.5% of the net UK electricity production and all wind energy 2.5% globally.

Photo: http://www.utility-exchange.co.uk/wp-content/uploads/2011/12/Offshore-Wind-Farm6.jpg



Option 3 **New market mechanism**

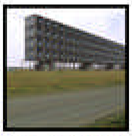
This low carbon energy option is defined by a focus on developing a new market-based mechanism in order to mitigate climate change. This could be realised through improving the uptake of a regulated 'cap and trade' system whereby countries that emit less than their greenhouse-gas emissions quota can sell credits to those that emit more. Several carbon markets are currently in operation around the world as a result of the Kyoto Protocol, including the EU Emissions Trading System. Photo: http://www.buydearborn.com/stock-market.jpg



Option 4 **Biochar**

This carbon climate geoengineering proposal is defined by a focus of research and demonstration of the application of biochar to soils (carbon that is locked away in the solid form of charcoal; the product of burnt biomass). Biochar is already used on a small scale in some agricultural practices to enhance crop yields. A number of start-up companies around the world are currently field trialling small scale biochar application to sequester carbon dioxide.

Photo: http://www.ens-newswire.com/ens/dec2008/20081217_biochar.jpg



Option 5 **Air capture and storage**

This carbon climate geoengineering proposal is defined by a focus on research into the use of technology for capturing carbon dioxide from the ambient air and sequestering it as a highly pressurised liquid form in underground geological reservoirs (e.g. depleted oil and gas wells). Large air capture units could be used to achieve this goal. A number of start-up companies around the world are currently field trialling small scale air capture technology.

Artist's impression: Carbon Engineering Ltd.

Continues overleaf

Option 6 Stratospheric aerosol injection

This solar climate geoengineering proposal is defined by a focus of research into the injection of sulphate particles into the stratosphere in order to reflect some sunlight back into space. This proposal could use a variety of delivery mechanisms, including pipes held aloft by tethered balloons; high-flying military aircraft; or surface-to-air missiles. A number of desk-based experiments have been conducted, but the world's first attempt to test the tethered balloon delivery mechanism was recently cancelled owing to governance deficiencies.

Photo: https://c479107.ssl.cf2.rackcdn.com/files/4249/width498/IMG_0814.jpg

Option 7 Business as usual

This option of inaction is defined by a focus on continuing business as usual, with no further adoption of any options for responding to global warming. This is realised through a continued heavy reliance on and consumption of fossil fuel energy sources, which currently represents approximately 88% of UK energy consumption and 87% globally. Despite those existing efforts to mitigate climate change, global temperatures have risen almost 1°C above pre-industrial levels.

Photo: http://media-2.web.britannica.com/eb-media/41/91841-004-8428B48T.jpg

Discretionary options overleaf

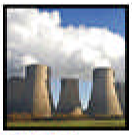
University of East Anglia Tyndall°Centre for Climate Change Research IAGP Integrated Assessment of Geoengineering Proposals 3S Science, Society & Sustainability

'Discretionary' options for tackling global warming – to be appraised if desired

Option 8 Nuclear fission energy

This low carbon energy option is defined by a focus on increasing the proportion of the world's energy that is provided by nuclear electricity in order to mitigate climate change. This could be realised by increasing the removal of barriers to delivery (e.g. in the planning system) and through increasing direct investment. Nuclear fission energy currently represents approximately 8% of UK energy consumption and 5% globally.

Photo: http://www.gfvvp.co.uk/photos/sizewell-nuclear-power-station.jpg



Option 9 Coal energy with carbon capture and storage

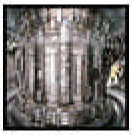
This low carbon energy option is defined by a focus of research and demonstration of the use of technology for capturing carbon dioxide before it is released from coal power stations and sequestering it as a highly pressurised liquid form in underground geological reservoirs (e.g. depleted oil and gas wells). A number of industrial scale experiments are underway with more planned.

Photo: http://static.guim.co.uk/sys-images/Guardian/Pix/pictures/2009/4/13/1239621514127/6.one-coal-fired-Ratcliff-001.jpg

Option 10 Carbon tax

This low carbon energy option is defined by a focus on broadening and increasing the taxation of carbon dioxide emitted during the fuel cycle in order to mitigate climate change. This could be realised by taxing currently untaxed components of the fuel cycle (e.g. industry). Carbon taxes are already in use, including the UK's Fuel Duty Escalator which applies to the transport sector.

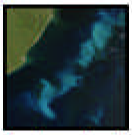
Photo: http://www.earthtimes.org/newsimage/radical-eu-carbon-tax-baby-steps_154.jpg



Option 11 Nuclear fusion energy

This low carbon energy option is defined by a focus of research into the use of potentially limitless fusion energy generation in order to mitigate climate change. This could be realised through the use of magnetic confinement. Many desk- and lab-based experiments have taken place and are ongoing.

Photo: European Fusion Development Agreement



Option 12 Iron fertilisation

This carbon climate geoengineering proposal is defined by a focus of research into the application of the nutrient iron to the ocean in order to stimulate algal growth and enhance the transfer of carbon to the deep ocean. Conventional ships could be used as a delivery mechanism. A number of oceanic experiments have been conducted, but questions about their legality are now raised by the London Convention ('Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter) and a moratorium adopted by the UN Convention on Biological Diversity.

Photo: http://earthobservatory.nasa.gov/IOTD/view.php?id=5298

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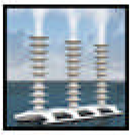
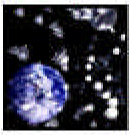


Option 13 Cloud albedo enhancement

This solar climate geoengineering proposal is defined by a focus of research into the use of technology to make cloud droplets appear brighter; by spraying sea salt to increase the number of cloud droplets and increase cloud reflectivity to sunlight. Automated ships could be used as a delivery mechanism for this proposal. A few desk-based experiments have been conducted, but no field experiments have yet taken place.

Artist's impression: John McNeill



Option 14 Space reflectors

This solar climate geoengineering proposal is defined by a focus of research into the use of mirrors in Earth orbit in order to reflect some sunlight back into space. This could be realised through launching trillions of small mirrors into space. A few desk-based experiments have been conducted, but no field experiments have yet taken place.

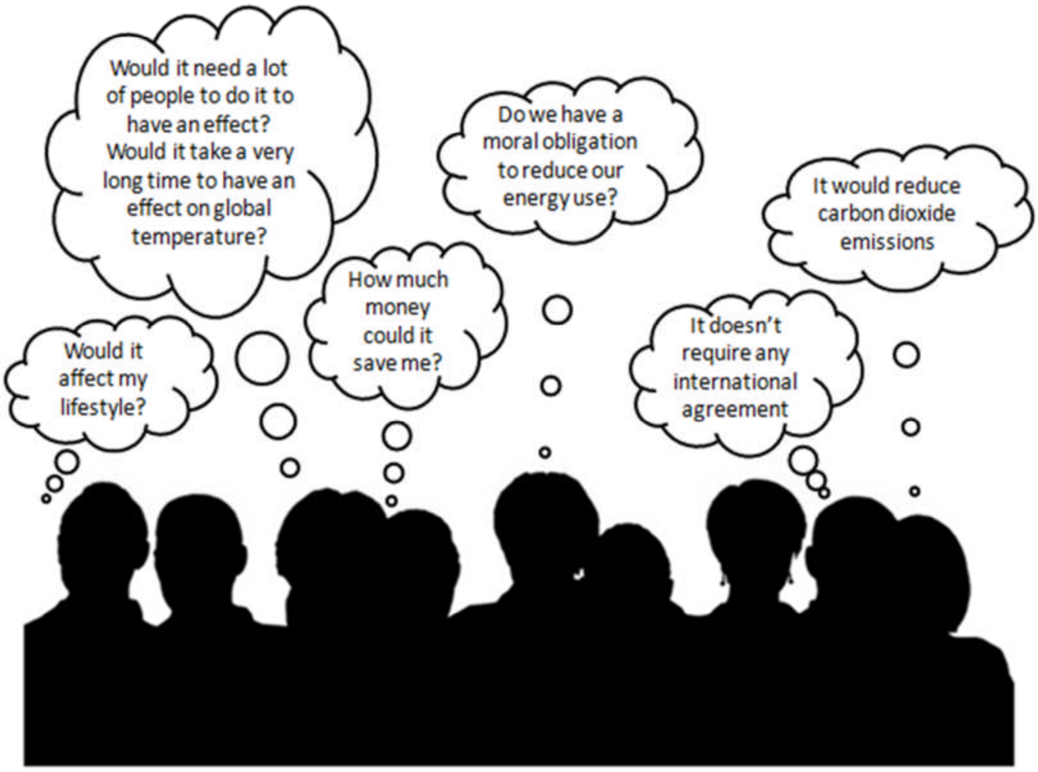
Artist's impression: http://howisearth.files.wordpress.com/2010/01/geoengineering-planet-earth-against-global-warming-mirrors-glass-discs-in-space.jpg

Appendix 1.1.3 Citizen Options Booklet

Option #1

Low carbon living

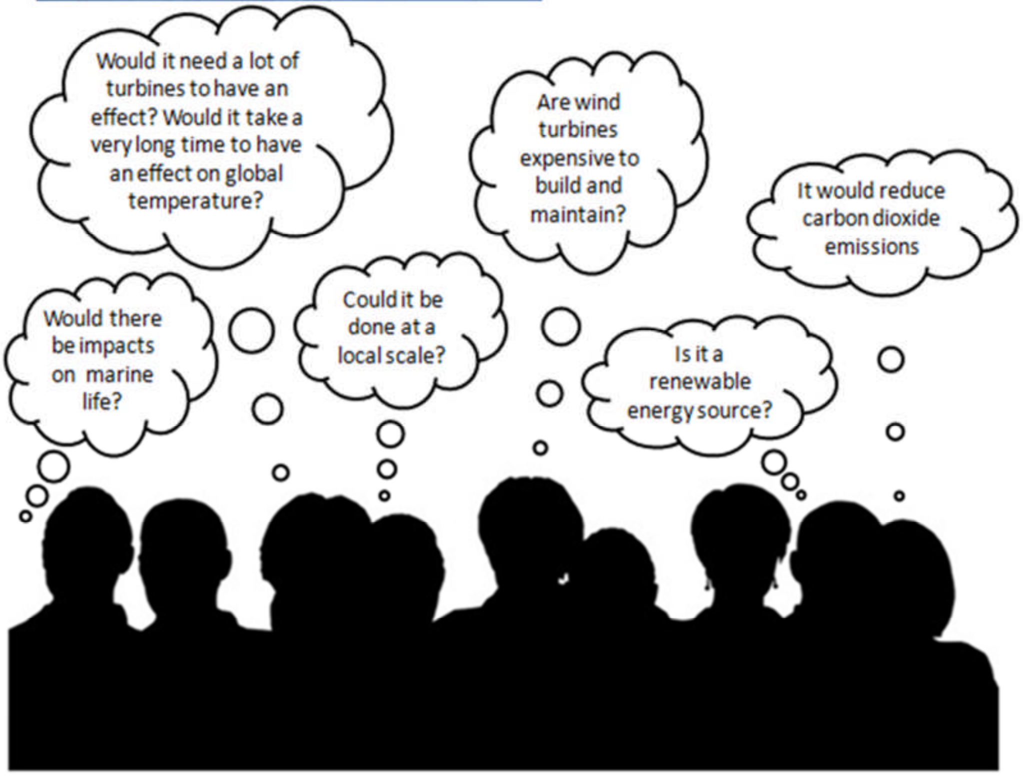
This energy saving option is defined by a focus on encouraging voluntary reductions in household and business energy use. This could be done through advertising and using 'smart' energy meters that monitor energy use. A number of advertising campaigns have already happened (for example, the UK's 'Act on CO_2' campaign), and smart meters are being tested before a nationwide roll-out.



Option #2

Offshore wind

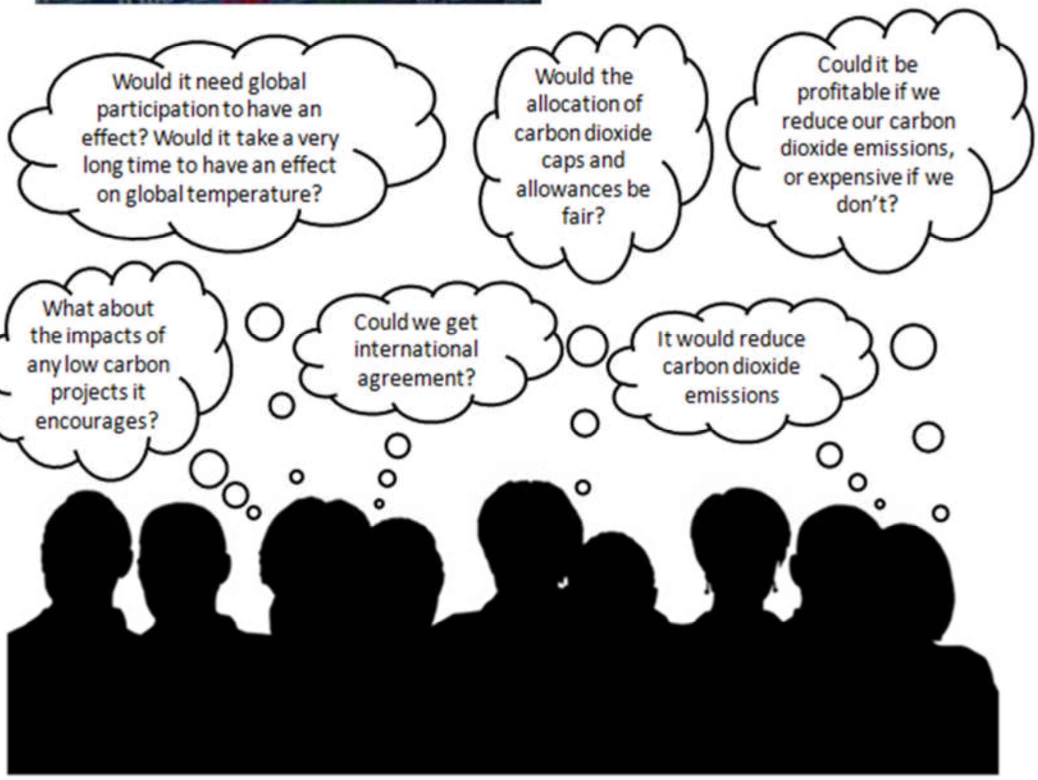
This low carbon energy option is defined by a focus of increasing the proportion of energy that is created by offshore wind. This could be done by removing barriers to development in the planning system or through increasing direct investment in offshore wind projects. Offshore wind energy currently supplies about 1.5% of the UK's energy, and globally less than about 2.5%.



Option #3

Carbon market

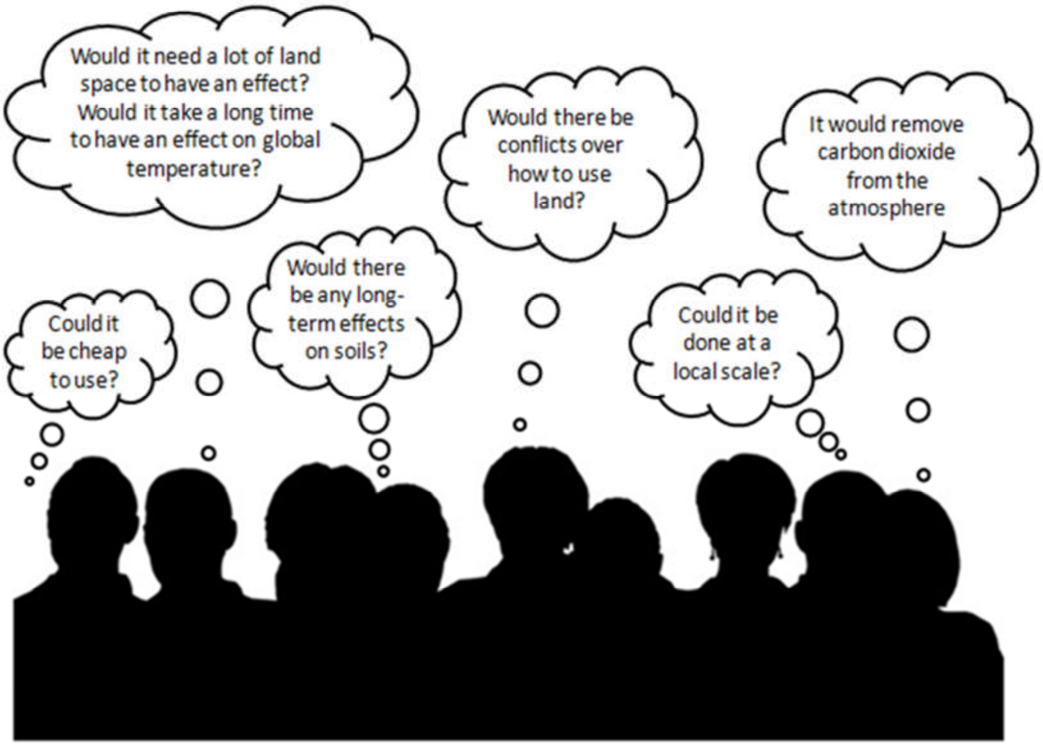
This economic option is defined by a focus on creating a new international market for trading carbon. This could be done by improving the existing 'cap and trade' system where countries that produce less than their carbon dioxide allowance can sell 'credits' to those that produce more. Several carbon markets already exist, including the European Union Emissions Trading System.



Option #4

Biochar

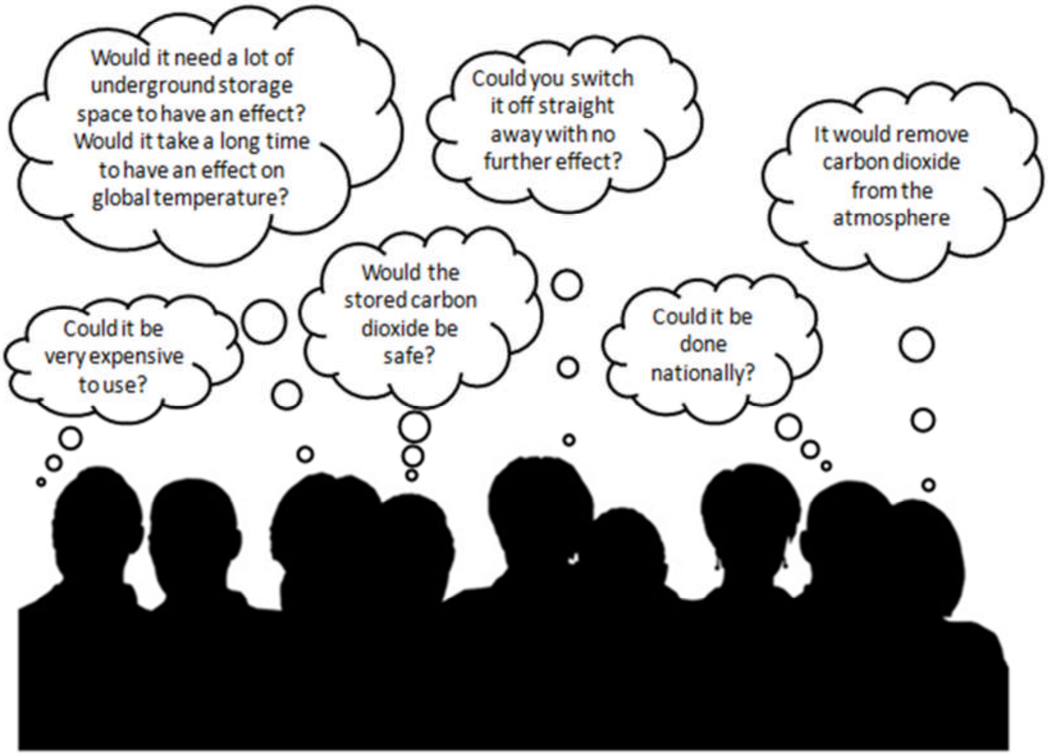
This carbon climate geoengineering proposal is defined by a focus of research and use of burning biomass to make carbon-rich charcoal ('biochar') and putting it into soils. Biochar is already used in some small agricultural practices to improve crop yields. A number of new companies around the world are testing biochar as a way to store carbon dioxide underground.



Option #5

Air capture

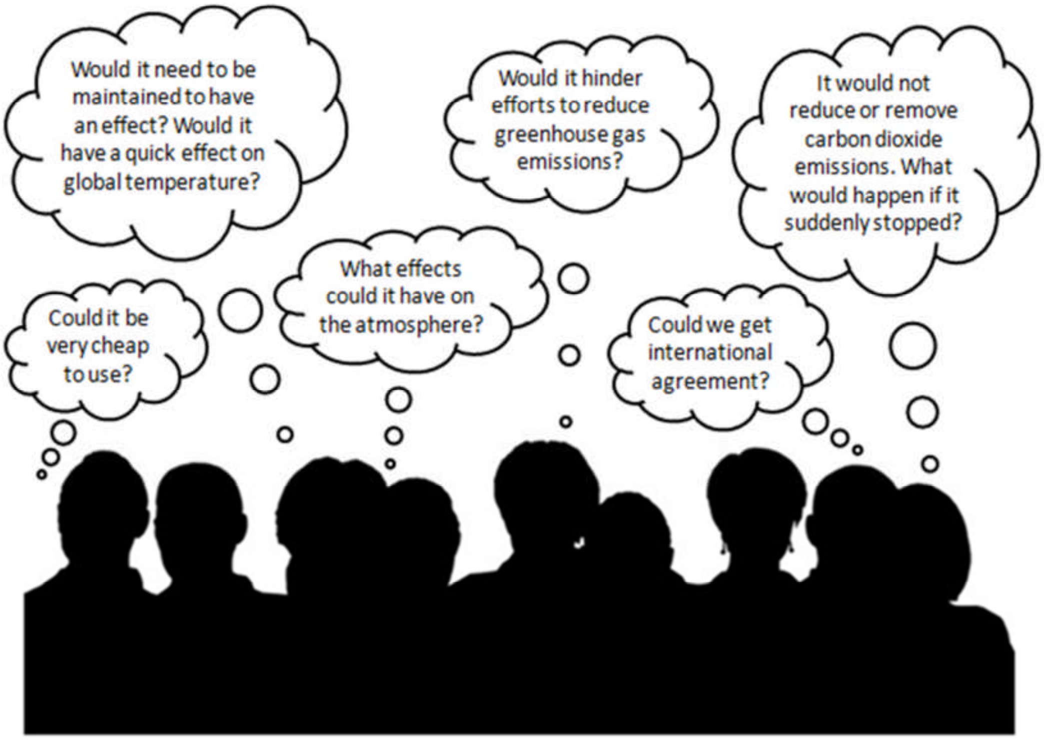
This carbon climate geoengineering proposal is defined by a focus of research into capturing carbon dioxide from the air and storing it underground (for example, in used oil and gas wells). This could be done by building large air capture units. A number of new companies around the world are currently testing small air capture technology.



Option #6

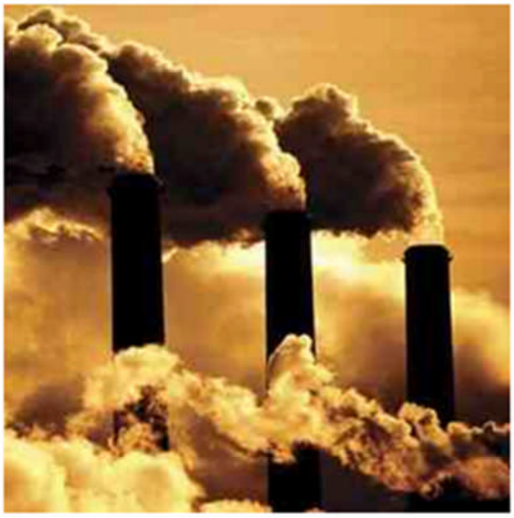
Sulphate particles

This solar climate geoengineering proposal is defined by a focus of research into putting sulphate particles into the atmosphere in order to reflect some sunlight back into space. This could be done by pumping the particles up a tall pipe attached to a balloon; by spraying the particles from high-flying military aircraft; or by launching the particles in surface-to-air missiles. Scientists have done a number of desk-based studies, but the world's first attempt to test the equipment needed for pumping particles up a pipe attached to a balloon was recently cancelled because of lacking international decision making arrangements.

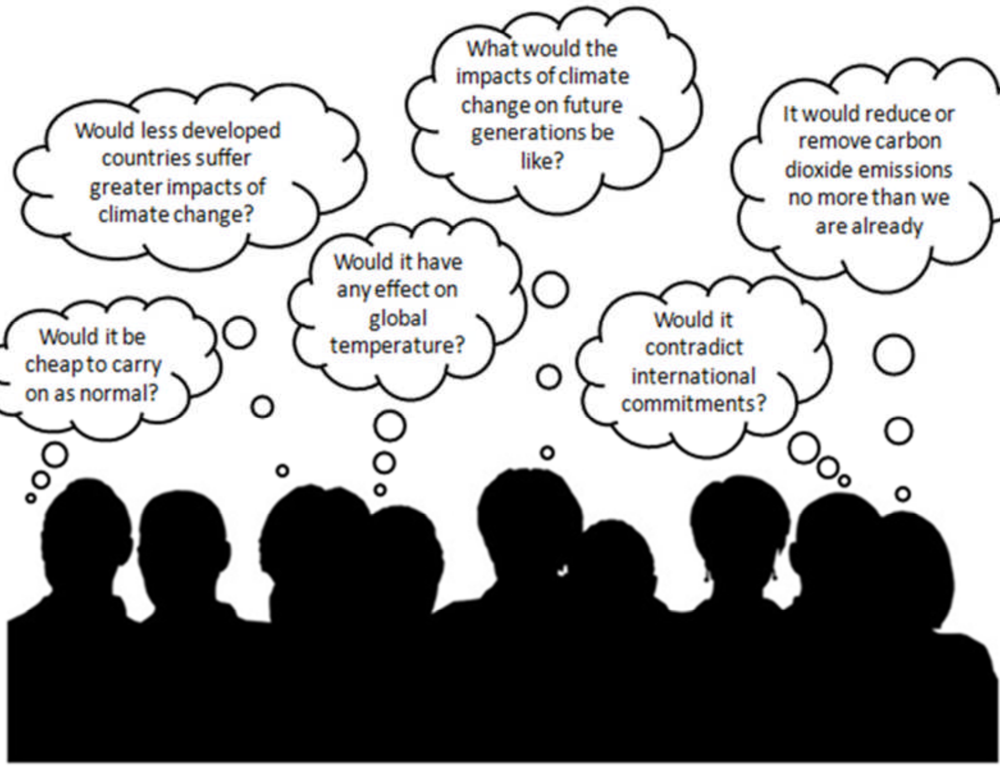


Option #7

Business as usual



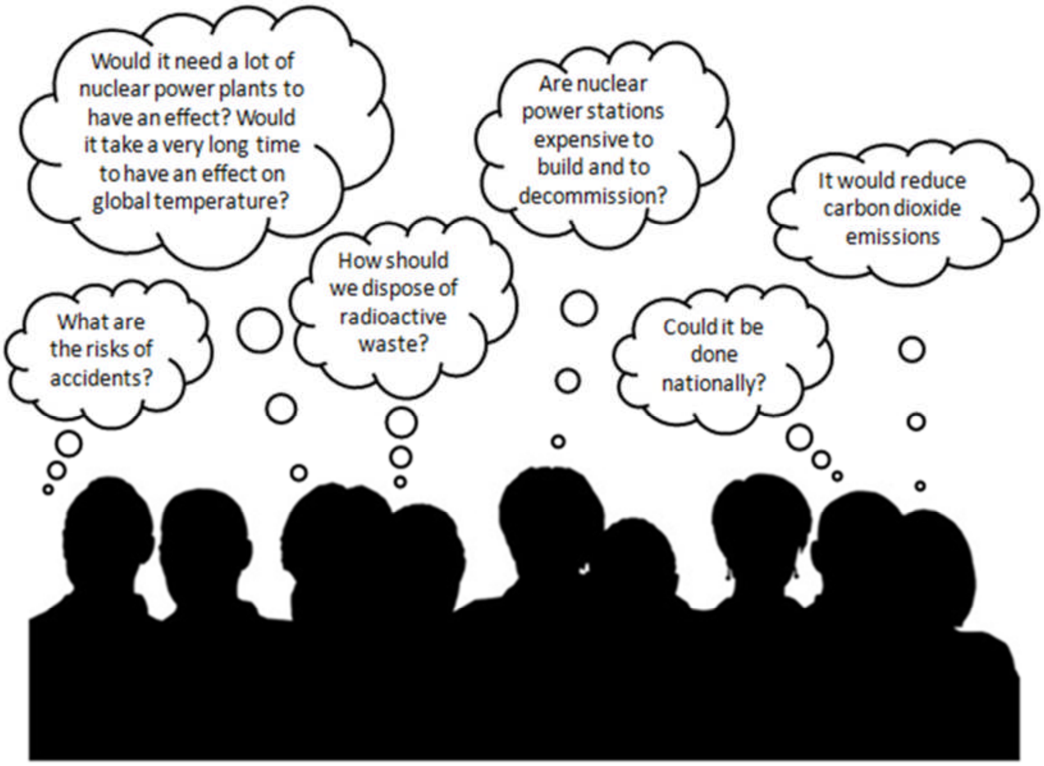
This option of inaction is defined by a focus of continuing business as usual, with no further use of options for tackling global warming. This would involve a continued heavy reliance on fossil fuel energy sources (coal, oil and gas). 88% of the energy used in the UK is from fossil fuels and 87% globally. Despite existing efforts to tackle global warming, global temperatures have risen almost 1°C since before the industrial revolution in about 1750.



Option #8

Nuclear energy

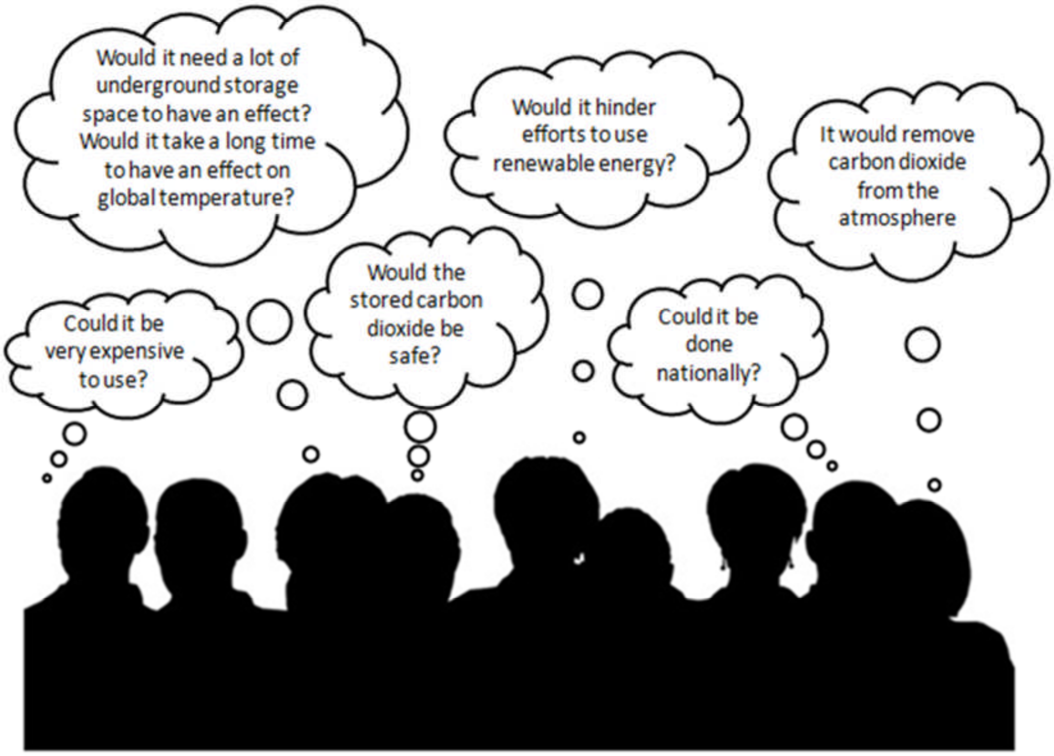
This low carbon energy option is defined by a focus on increasing the proportion of energy that is created by nuclear energy. This could be done by removing barriers to development in the planning system or through increasing direct investment in nuclear energy projects. 8% of the energy used in the UK is from nuclear energy and 5% globally.



Option #9

Clean coal

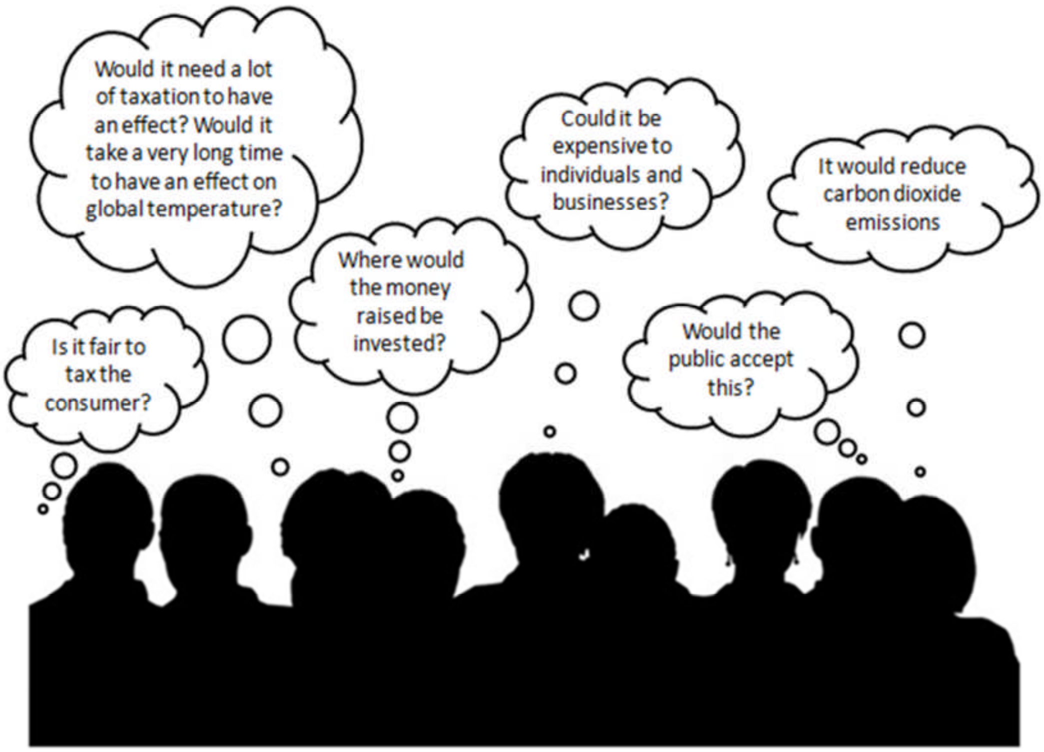
This low carbon energy option is defined by a focus of research and use of technology for capturing carbon dioxide from coal power stations before it is released and storing it underground (for example, in used oil and gas wells). A number of large tests are underway and more are planned.



Option #10

Carbon tax

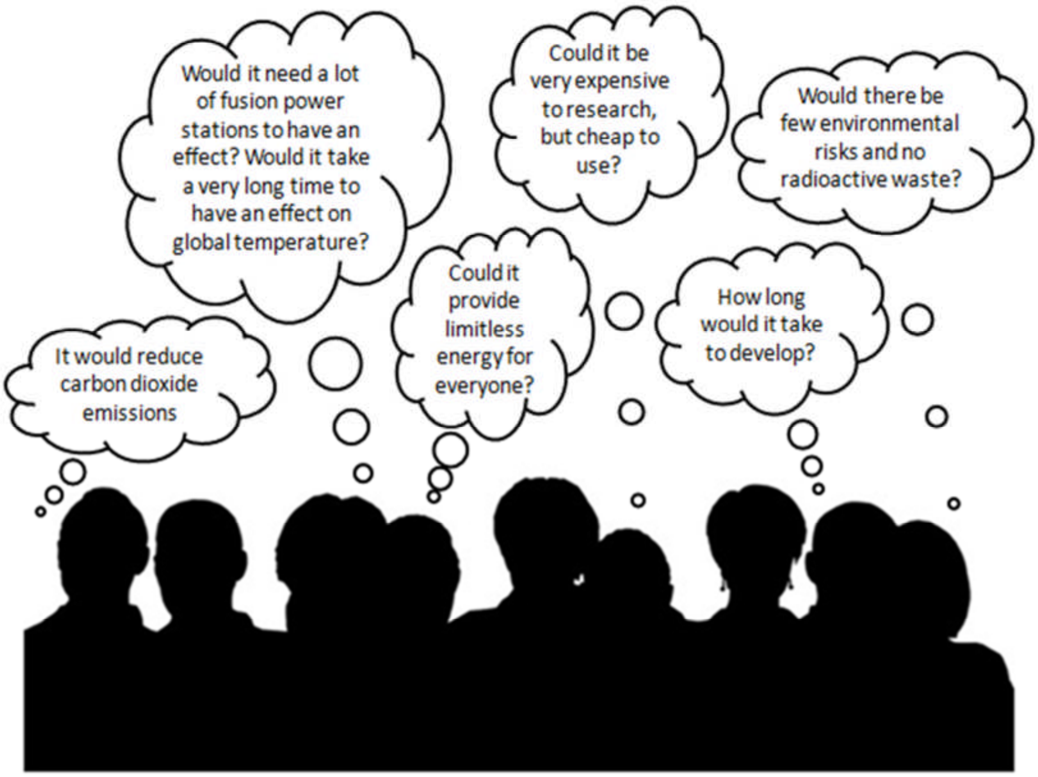
This economic option is defined by a focus on increasing the taxation of carbon dioxide released by fuel use. This could be done by taxing currently untaxed sectors such as industry. Carbon taxes are already in use, including the UK's Fuel Duty Escalator which applies to the transport sector.



Option #11

Fusion energy

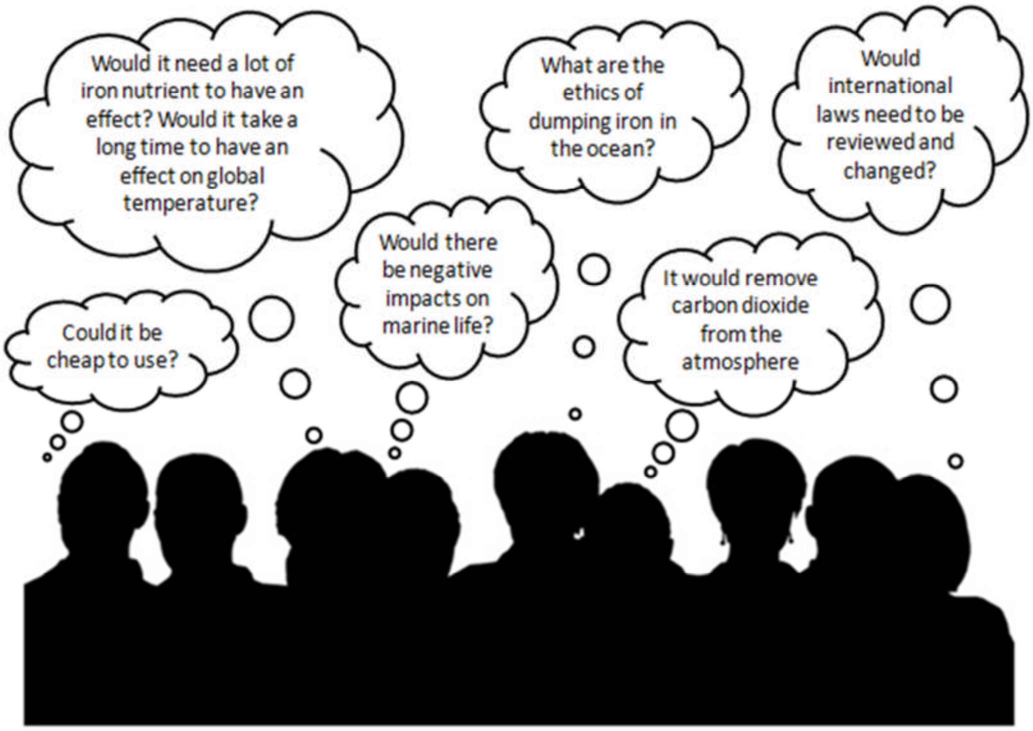
This low carbon energy proposal is defined by a focus of research into the use of potentially limitless fusion energy. This could be done by using a process called magnetic confinement. Scientists have done many desk-based studies and laboratory tests which are ongoing.



Option #12

Ocean fertilisation

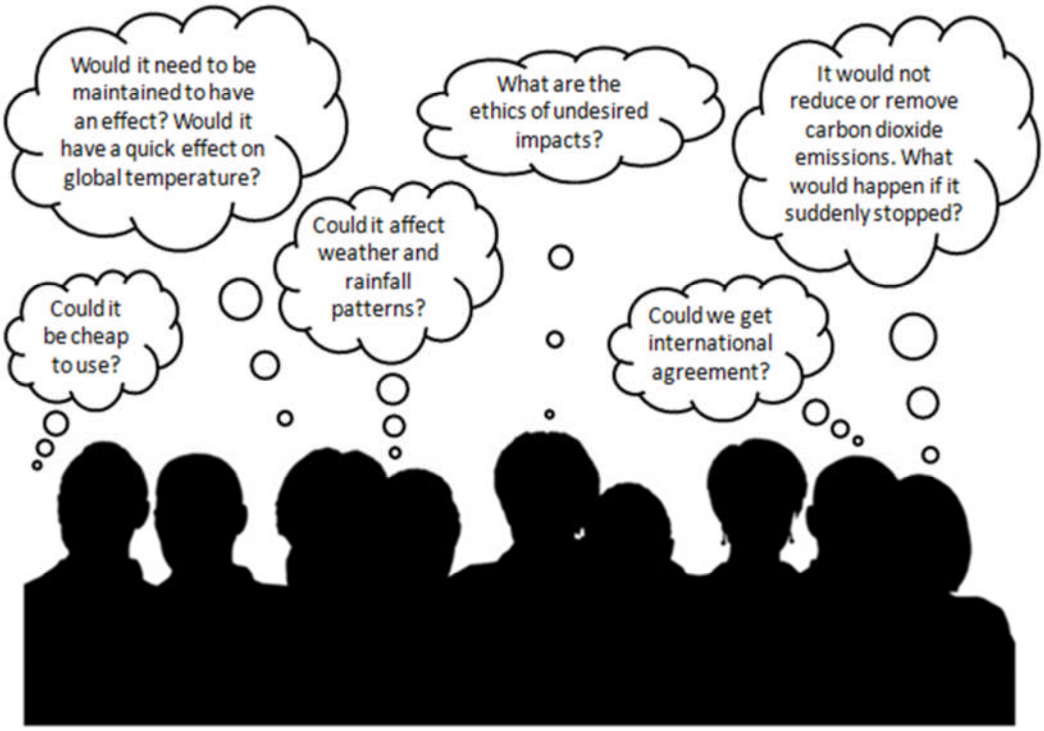
This carbon geoengineering proposal is defined by a focus of research into the dumping of iron nutrient into the ocean to encourage algal growth, in order to absorb more carbon dioxide and store it in the ocean. This could be done using conventional ships. A number of tests have been done in the oceans, but there are questions about their legality.



Option #13

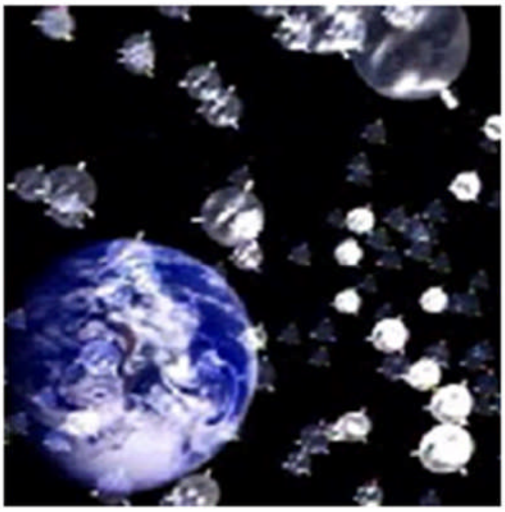
Cloud brightening

This solar geoengineering proposal is defined by a focus of research into the use of technology to make clouds brighter, in order to reflect some sunlight back into space. This could be done by using automated ships to spray sea salt into the air to increase the number of cloud droplets. A few desk-based studies have taken place.

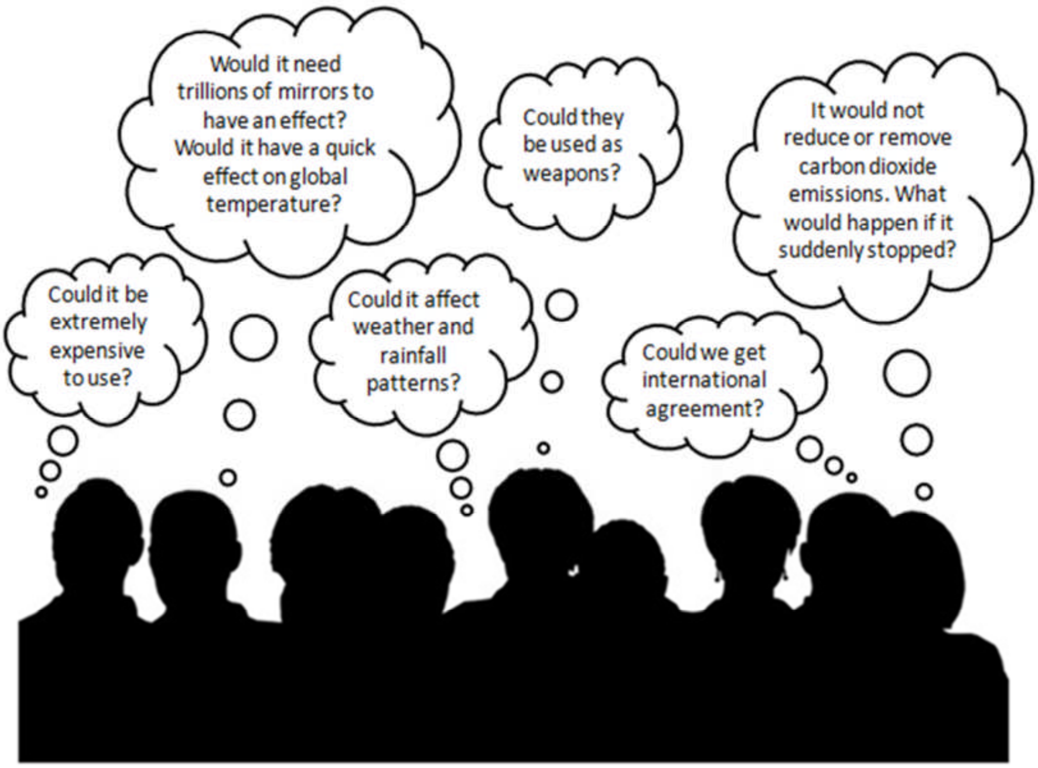


Option #14

Space mirrors



This solar geoengineering proposal is defined by a focus of research into the use of mirrors in Earth orbit, in order to reflect some sunlight back into space. This could be done by launching trillions of small mirrors into orbit. A few desk-based studies have taken place.



Appendix 1.2 Participant recruitment

Appendix 1.2.1 Specialist Telephone Interview Protocol

Specialist and stakeholder participants in the scoping interviews will be contacted via e-mail prior to the telephone interviews in order to arrange a convenient time.

Telephone interview part 1

Participants will be invited to partake in a scoping interview with the aim of identifying participants for inclusion in a study on appraising climate geoengineering. The aim of this study is to appraise geoengineering proposals relative to the other options for tackling climate change – spanning mitigation and adaptation. Participants will be selected on the basis of their personal as well as disciplinary perspectives.

The study is being conducted by me, Rob Bellamy, under the supervision of Dr. Jason Chilvers, Dr. Nem Vaughan and Professor Tim Lenton. The study is affiliated to the University of East Anglia, the Tyndall Centre for Climate Change Research, the Science Society and Sustainability (3S) research group and the Integrated Assessment of Geoengineering Proposals (IAGP) project.

The scoping interview should be short and last only between 15 – 30 minutes. If selected for participation in the full study, participants will be required to engage with two Multi-Criteria Mapping (MCM) interviews lasting between 2 – 3 hours. In addition to these interviews, some participants will be called upon to partake in the half-day joint workshop to interact with citizens.

Participants in the scoping interviews will remain anonymous and their data secure and confidential. Participants will be asked about their personal and disciplinary perspectives on geoengineering:

- How often do you encounter the idea of geoengineering in your profession?
- Can you tell me a bit about the nature of those encounters?
- Do you support or oppose research into climate geoengineering proposals?
- Can you tell me a bit about why you hold that position?

Finally, participants will be asked if they have any general questions or observations about the study.

Telephone interview part 2

Those selected for inclusion in the full study will be asked to arrange a convenient time for the first MCM interviews, to be held at their place of work. They will be alerted to the dispatch of an interview briefing package which includes an introduction to MCM and the 'core' options for appraisal. Participants not selected for inclusion in the study will be thanked for their time and contribution.

Appendix 1.2.2 Citizen Online Survey Protocol

Email subject: Participate in research on tackling global environmental issues and earn £80 M&S vouchers

Dear Sir / Madam,

Would you like to participate in research on global environmental issues and earn £80 in M&S vouchers?

Researchers at the University of East Anglia are looking for 18 people from across Norfolk to participate in the two-day study, which includes lunch and refreshments and covers travel expenses. Potential participants must be available to attend both days:

- Saturday 4th August 2012 from 9:30am – 4:00pm at Yours Business Networks in King's Lynn
- Saturday 11th August 2012 from 9:30am – 4:00pm at the University of East Anglia in Norwich

If you can make your own way to these locations travel expenses will be reimbursed (car, bus, train). Arranged transport to King's Lynn on Saturday 4th August will be available for those going from / able to get to Norwich.

Please complete this short questionnaire before Thursday 12th July to register your interest: http://www.surveymonkey.com/s/775L6NR

Selected participants will be notified and invited on Monday 16th July.

Kind regards,

Rob Bellamy

Doctoral Researcher
School of Environmental Sciences
University of East Anglia, Norwich Research Park
Norwich, NR4 7TJ
E: r.bellamy@uea.ac.uk
T: (01603) 591346

Welcome,

Thank you for taking time to complete this survey, which is being conducted by Rob Bellamy, a researcher based at the University of East Anglia. The aim of the survey is to find out about your views on global environmental issues.

The survey should take no longer than 10 minutes to complete, and all data collected will be held securely and will not be used for any other purpose.

By participating in this survey and leaving your contact details you will be considered as a potential participant in a two-day study on global environmental issues. Selected participants will earn

£80 M&S vouchers for their time. Lunch and refreshments will also be provided and travel expenses covered by the University of East Anglia.

PLEASE NOTE THAT THIS SURVEY WILL CLOSE ON FRIDAY 16TH JULY (THIS FRIDAY)

Selected participants will be notified and invited on Monday 16th July.

Please select one answer for each question.

1. What is your gender?

- Male
- Female

2. Which age group do you belong to?

- 18 - 24
- 25 - 44
- 45 - 64
- 65+

3. Which occupational group best describes the occupation of your household's chief income earner? The chief income earner is the person in your household with the largest income. If the chief income earner is retired and has an occupational pension; or is not in employment and has been out of work for less than six months please answer for their most recent occupation.

- Semi or unskilled manual work (e.g. Manual workers, all apprentices to be skilled trades, Caretaker, Park keeper, non-HGV driver, shop assistant)
- Skilled manual worker (e.g. Skilled Bricklayer, Carpenter, Plumber, Painter, Bus/ Ambulance Driver, HGV driver, AA patrolman, pub/bar worker, etc)
- Supervisory or clerical/ junior managerial/ professional/ administrative (e.g. Office worker, Student Doctor, Foreman with 25+ employees, salesperson, etc)
- Intermediate managerial/ professional/ administrative (e.g. Newly qualified (under 3 years) doctor, Solicitor, Board director small organisation, middle manager in large organisation, principle officer in civil service/local government)
- Higher managerial/ professional/ administrative (e.g. Established doctor, Solicitor, Board Director in a large organisation (200+ employees, top level civil servant/public service employee)
- Student
- Casual worker – not in permanent employment
- Housewife/ Homemaker
- Retired and living on state pension
- Unemployed or not working due to long-term sickness
- Not working due to disability
- Full-time carer of other household member

4. Do you have any special dietary requirements?

- Yes
- No
- If yes, please write in details

5. Can you make your own way to King's Lynn on Saturday 4th August or would you like to use the arranged transport from Norwich?

- I can make my own way by car, bus or train
- I would like to travel to Norwich and use the arranged transport to King's Lynn

6. In your opinion, which of the following do you consider to be the most serious issue currently facing the world as a whole?

- A major global economic downturn
- Armed conflicts
- Climate change
- International terrorism
- Poverty, lack of food or drinking water
- The increasing world population
- The proliferation of nuclear weapons
- The spread of infectious diseases
- Other, please write in details

7. Which of the following best describes your preferred approach for tackling global environmental issues?

- Global environmental issues should be managed by experts
- Global environmental issues should be corrected using economic markets
- Global environmental issues should involve everyone doing their part
- We should not intervene in global environmental issues, they are too unpredictable

8. In your opinion, which of the following best describes the causes of climate change?

- Climate change is entirely caused by natural processes
- Climate change is mainly caused by natural processes
- Climate change is partly caused by natural processes and partly caused by human activity
- Climate change is mainly caused by human activity
- Climate change is entirely caused by human activity
- There is no such thing as climate change
- Don't know

9. Are you a member of an environmental charity or campaigning organisation?

- Yes
- No
- If yes, please write in details

10. Please enter your daytime telephone number and email address so that we may contact you about participating in the study

Appendix 1.2.3 Citizen Apportionment

	NS-SEC 1 – 3 (36%) 5.04 (6)‡	NS-SEC 4 – 9 (64%) 8.96 (8)
18 – 24 (11%) 1.54 (2)†	P1(F)	—
25 – 44 (24%) 3.36 (3)	P2(M); P3(F)	P4(M)
45 – 64 (2%) 3.78 (4)	P5(M); P6(F)	P7(M), P8(F)*; —
65+ (21%) 2.94 (3)	P9(M)+; P10(F)	P11(M); P12(M); P13(F)

Fourteen sociodemographically representative participants were sought, of which two were later unable to attend (denoted –), and for which one was replaced, albeit in a different age and NS-SEC grouping (denoted +); and one was unable to attend the second citizens' panel (denoted *). † Column format as example follows: 18 – 24 [age group] (11%) [% proportion of sample] 1.54 [proportion of fourteen participants] (2) [proportion rounded to nearest whole number]. ‡ Row format as example follows: NS-SEC 1 – 3 [NS-SEC grouping] (36%) [% proportion of sample] 5.04 [proportion of fourteen participants] (6) [proportion rounded to nearest whole number]. Participant codes as example follows: P1 [Participant 1] (F) [female].

Appendix 1.2.4 Participant consent forms (specialist then citizen)

PARTICIPANT CONSENT FORM

University of East Anglia

Project title: APPRAISING GEOENGINEERING

Rob Bellamy
Doctoral Researcher
School of Environmental Sciences
University of East Anglia, Norwich Research Park
Norwich, NR4 7TJ
E: r.bellamy@uea.ac.uk
T: (01603) 591346

Please read the following carefully and mark an 'X' in each box:

I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions. ☐

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving reason. ☐

I agree to the interview being audio recorded. ☐

I agree to the use of my name / position / organisation / anonymous quotes in publications arising from this study (delete as appropriate). ☐

I agree that my data gathered in this study may be stored in a secure data centre and may be used for future research. ☐

I agree to take part in the above study. ☐

Name of participant	Date	Signature
Name of researcher	Date	Signature

PARTICIPANT CONSENT FORM

University of East Anglia

Project title: APPRAISING GEOENGINEERING

Rob Bellamy
Doctoral Researcher
School of Environmental Sciences
University of East Anglia, Norwich Research Park
Norwich, NR4 7TJ
E: r.bellamy@uea.ac.uk
T: (01603) 591346

Please read the following carefully and mark an 'X' in each box:

I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions. ☐

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving reason. ☐

I agree to the interview being audio recorded. ☐

I agree to the use of anonymous quotes in publications arising from this study. ☐

I agree that my data gathered in this study may be stored in a secure data centre and may be used for future research. ☐

I agree to take part in the above study. ☐

Name of participant	Date	Signature
Name of researcher	Date	Signature

Appendix 1.3 Interview and workshop protocols

Appendix 1.3.1 First Multi-Criteria Mapping interview protocol (abridged)

MULTI-CRITERIA MAPPING INTERVIEW PROTOCOL

Before the interview (0 - 10 minutes)
- Introductions
- Complete participant consent form
- Set up audio recorders
- Set up laptop and software
- Ensure participant is familiar with 'core' options for appraisal

Interview step 1: select options (10 - 20 minutes)
- Reiterate that the options represent a range of possible strategies, technologies, policies or other courses of action that might be pursued in order to respond to global warming
- All 'core' options must be appraised by all participants; whilst 'discretionary' options or other self-defined options or option combinations can be appraised if desired
- Elicit initial reactions to each of the 'core' options, and any selected 'discretionary' and self-defined options
- Ask whether there are any obvious gaps in the set of core options
- Advise no more than 2 'discretionary' or self-defined options in addition to the 7 'core' options to begin

Interview step 2: define criteria (20 - 40 minutes)
- Explain that criteria are the different factors that the interviewee has in mind when they evaluate the relative pros and cons of each option
- Ensure criteria are clear and without overlaps and interdependencies
- Advise between 4 - 6 criteria to begin with; less is too broad and more can be added later
- Back up file

Interview step 3: assess scores (40 - 100 minutes)
- This involves the relative evaluation of each of the options against each of the criteria, and is the most time-consuming part of the interview
- Use a scale of 0 - 10, where low scores always represent a poor performance and high scores represent a good performance
- Enter a 'pessimistic' (worst-case scenario) and 'optimistic' (best-case) scenario score for each option under each criterion to represent any uncertainty, variability or sensitivity; if there is no uncertainty enter the same number in each box
- These scores should reflect what the interviewee considers to be 'reasonably likely'
- Makes note of all assumptions associated with uncertain, variable or sensitive scores
- Check the graphic above the scoring for each criterion accurately reflects the interviewees judgements; if it does not and they wish to make and amendment, ask why and proceed
- Back up file

Interview step 4: assign weightings (100 - 120 minutes)
- Minimise the graphic panel initially
- Explain that this involves 'weighting' or valuing the relative importance of each of the criteria
- Explain that the graphic represents the relative performance of every option under every criterion
- Does the initial weighting graphic hold any surprises for them? Do some options perform higher or lower than expected? Why might this be?
- Interviewees are free to alter the rankings if they wish - MCM is a 'heuristic' (a way of exploring the issue).
- The final objective is that interviewees arrive at a final ranking picture, which satisfies them as a reasonable expression of their own particular view on the relative merits of the different options - bearing in mind that it is limited by the information available at the time and is a 'snapshot' and subject to change
- Reflection on the process: how reasonable does it seem as a way to elicit and explore their views; were there any aspects they particularly liked or disliked?
- Back up

After the interview
- Back up MCM files and audio files

University of East Anglia · Tyndall°Centre for Climate Change Research · IAGP Integrated Assessment of Geoengineering Proposals · 3S Science, Society & Sustainability

Appendix 1.3.2 Second Multi-Criteria Mapping interview protocol

Before the interview (0 - 5 minutes)

- Introductions
- Set up audio recorders
- Set up laptop and software

Interview step 1: Review the other appraisals (5 - 25 minutes)

- Familiarise the participant with the criteria and scores given by other specialists and the citizens' panels.
- Encourage participants to vocalise their reactions to the other appraisals, whilst reflecting on their own.

Interview step 2: Elicit any changes to own appraisal (25 - 35 minutes [+30 minutes if needed])

- Reflect explicitly on the participant's own appraisal and elicit any desired changes to their criteria and scores, as well as asking if they would like to appraise any further options (including those additional options proposed by other specialists)

Interview step 3: Future (35 - 50 minutes)

- Ask the participant for comments on the future of geoengineering
- Are there comments on any specific geoengineering proposals?
- Ask the participant for comments on the future of how geoengineering should be appraised
- Ask the participant for comments on the future of how geoengineering should be governed

Interview step 4: Process evaluation (50 - 60 minutes)

- Ask the participant for comments about the overall process and its performance
- Ask the participant for reflections on what they have learned and gained from the process
- Ask the participant about their expectations of policy outcomes
- Ask the participant for any other comments
- After the interview
- Back up MCM files and audio files

Appendix 1.3.3 First Citizens' Panel protocol

Citizens' panel (1)

Saturday 4th August 2012; 09:30 - 16:00; Yours Business Networks, King's Lynn

Research team: Rob Bellamy (RB), Jason Chilvers (JC) and Kate Porter (KP)

Venue coordination: Marianne (M)

Participants: 14 citizens

RB mobile number: 07528 024588

JC mobile number: 07790 400297

KP mobile number: 07725 558583

Aims and objectives

- To allow participants to frame the issue of global warming and how to tackle it
- To explore participant reactions to 'main' and selected 'optional' as well as self-defined options for tackling global warming
- To elicit criteria for the evaluation of those options
- To formulate questions to pose in the second workshop

Before the workshop

- Set up in King's Lynn on Friday afternoon: bring all equipment and materials and set-up; arrange layout (registration desk in lunch area; horseshoe in main room; round table in break out rooms, put white tac on posters ready to put up the next day) [**RB**]
- Travel to venue in time for opening at 9:00am [**RB & M**)
- Taxi travel to Norwich convene at bus stop opposite Norwich Theatre Royal for departure at 8:15 [**JC, 7 citizens**)

09:30 - 10:00 Registration

- Taxi arrival between 9:00 and 9.30 [**JC, KP**]
- Greet participants on arrival [**RB, JC, KP**]
- Register participants on arrival and give sticker name badges and workshop programme [**KP**]
- Tea and coffee served on arrival at 09:30 [**M**]
- Ask participants to complete consent forms, highlight anonymity [**RB & JC**]

- *MATERIALS: felt pens; pens; list of expected attendees to sign off on arrival; 22 stickers for name badges; 18 copies of the schedule for the day; 18 consent forms*

10:00 - 10:45 Welcome (plenary, led by **RB**)

- Welcome and introduce the research team [**RB**]
- Housekeeping before we start - make everyone aware of fire exit locations and toilets
- State the aim of the workshops - to participate in the evaluation of options for responding to global warming with the aim of producing a government policy brief
- State the role of the citizens: we want you to ask questions whenever you think of them, the facilitators are here to start discussions, but talking to each other is the main aim
- Any questions? Plus M&S gift cards will be given at the end of next week
- Ask participants to think of 5 ground rules for the day (e.g. respect for others' contributions; listen to what other people have to say; do not interrupt or criticise other people's points; punctuality to programme; take an active part; mobile phones on silent)
- Ice-breaker exercise - everyone to line up by birthday month and day, then in pairs spend 2 minutes learning one interesting thing about each other, and then sit down with your partner and report back to the group [**ALL**]
- *MATERIALS: N/A*

[30]

10:45 - 11:15 Framing the issue (plenary, facilitated by **RB**)

- When thinking about global environmental issues, what are the most important issues that come to mind?
- What comes to mind when thinking about global warming?
- What comes to mind when thinking about options for tackling global warming?
- Probe reasons as to why participants hold certain positions
- Periodically check audio recorders are on and working [**KP**]
- *MATERIALS: 2 audio recorders with boundary microphones; spare batteries*

11:15 - 11:30 Break

- Tea and coffee served [**M**]
- Affix posters to walls [**RB, JC, KP**]
- *MATERIALS: posters*

11:30 - 11:45 Presentation on global warming (plenary, given by **RB**)

- *MATERIALS: PowerPoint presentation*

15

11:45 - 12:00 Framing the issue (plenary, facilitated by **RB**)

- Did the presentation raise any other thoughts about global warming or options for tackling it?
- Probe reasons as to why participants hold certain positions
- Periodically check audio recorders are on and working [**KP**]
- *MATERIALS: 2 audio recorders with boundary microphones; spare batteries*

12:00 - 12:15 Presentation on 'main' and 'optional' options for tackling global warming (plenary, given by **RB**)

- *MATERIALS: PowerPoint presentation*

45

12:15 - 13:00 Exploring the options (♂ facilitated by **RB**, ♀ facilitated by **JC**)

- Give information booklets
- What are your first reactions to the options presented?
- What do you think about the reducing emissions options? What do you like / dislike about them?
- What do you think about the geoengineering proposals? What do you like / dislike about them?
- Are there any other options you would like to see?
- Probe reasons as to why participants hold certain positions
- Make notes on possible implicit criteria for reference to the next session
- Periodically check audio recorders are on and working [**KP**]
- *MATERIALS: 21 booklets; 2 audio recorders with boundary microphones; spare batteries*

13:00 - 14:00 Lunch

- Lunch served [**M**]
- Participants to view posters [**ALL**]
- *MATERIALS: N/A*

45

14:00 - 14:45 Developing the criteria (♂ facilitated by **RB**, ♀ facilitated by **JC**)

- Introduce what is meant by criteria - things to evaluate the performance of options by. Refer to the inferred criteria from 'likes' and 'dislikes' elicited in the previous session

- Develop a set of criteria on post-it notes individually (5 minutes)
- Amalgamate/combine the criteria on post-it notes in pairs (5 minutes)
- Amalgamate/combine the criteria on flip-chart paper as a group (20 minutes)
- Recruit 1-2 citizens to feed back their criteria clusters to the group in the next session
- Aim to produce a set of maximum 8 criteria
- Probe reasons as to what participants mean by their criteria
- Periodically check audio recorders are on and working [**KP**]
- *MATERIALS: 2 audio recorders with boundary microphones; spare batteries; flip chart paper; post-it notes; felt pens; pens*

[30]

14:45 - 15:15 Merging the criteria (plenary, facilitated by **RB**)

- Representatives of each group feed back their criteria in plenary, explaining what is meant by each criterion
- Explain that the aim is to produce a single set of coherent criteria for everyone to work with
- Are there any similarities between the criteria? Could we group any of them together?
- Facilitator to suggest categorical titles if needed, based on the citizens' deliberations
- Aim to produce a set of between maximum 6 - 7 criteria
- Periodically check audio recorders are on and working [**KP**]
- *MATERIALS: 2 audio recorders with boundary microphones; spare batteries; flip chart paper; felt pens*

15:15 - 15:30 Break

- Tea and coffee served [**M**]

[30]

15:30 - 16:00 Joint workshop preparation (plenary, led by **RB**)

- Introduce next week's joint workshop: need to come up with a set of questions for specialists (think about whilst undertaking this practice appraisal); recruit 1-2 citizens to talk about their experiences this week and lead the questions next week
- Periodically check audio recorders are on and working [**KP**]
- *MATERIALS: 2 audio recorders with boundary microphones; spare batteries; flip chart paper; practice appraisal poster; unique sticky dots; felt pens; pens*

15:45 - 16:00 Close (plenary, led by **RB**)

- Any questions or comments about the process so far?

- If you want to debate the issue during the week or think of any more questions to ask the experts please post them on our website, which will be online soon - the link will be included in the e-mail about how to get to next week's venue
- Next week's workshop will be held at the University of East Anglia, details on how to get there will be sent soon
- Thank you for your time, and we look forward to seeing you next week!

After the workshop

- Pack everything up (**RB, JC, KP**)
- Back up all data (**RB**)
- Taxi to return to Norwich (**JC, 7 citizens**)

Materials

- Scissors
- Sellotape
- Felt pens
- Pens
- 22 x stickers for name badges
- White tac
- Flip chart paper
- Post it notes
- 18 sets of unique sticky dots (90)
- Posters
- Poster carry tube
- 2 x audio recorders with boundary microphones
- Spare batteries
- List of expected attendees to sign off on arrival
- 18 copies of the schedule for the day
- 18 consent forms
- 21 booklets
- Travel expense claim forms
- PowerPoint presentation: Global warming
- PowerPoint presentation: Options
- Save each PPT in three formats: .ppt .pptx and .pdf

Appendix 1.3.4 Joint Workshop and Second Citizens' Panel protocol

Joint workshop and citizens' panel (2)

Saturday 22nd September 2012; 09:30 - 16:00; TPSC rooms 1.6 and 1.4, UEA

Research team: Rob Bellamy (RB), Kate Porter (KP) and Raquel Nunes (RN)

Participants: 13 citizens plus 2 specialists

Aims and objectives

- To facilitate participant interaction and learning with specialists, to test the knowledge and value claims of specialists, and to allow specialists to view citizen engagement with the issue
- To score the relative performances of 'main' and selected 'discretionary' and self-defined options for tackling global warming
- To weight the relative importance of the appraisal criteria
- To elicit evaluative comments about the performance of the Deliberative Mapping process

Before the workshop

- Set-up in TPSC 1.6 on Friday at 16:00 and TPSC 1.4 on Saturday morning: bring all equipment and materials and set-up; arrange layout (registration desk at TPSC entrance; horseshoe in TPSC 1.6 plus specialist fair tables and break out table and side break/lunch table; break out table in TPSC 1.4) [**RB**]
- Travel to venue in time for 8:30am [**RB, KP, RN**]

09:30 - 10:00 Registration

- Register participants on arrival and give sticker name badges and options booklet (keep this with you, you will need it later!) [**KP**]
- Greet participants on arrival [**RB, KP, RN**]
- Tea and coffee served on arrival at 09:30 [**Catering Direct**]
- *MATERIALS: felt pens; pens; list of expected attendees to sign off on arrival; 16 stickers for name badges; 3 copies of the schedule for the day; options booklets*

10:00 - 10:10 Welcome (plenary, led by **RB**)

- Everyone sat in horseshoe, specialists interspersed with citizens
- Welcome and introduce the research team, and the specialist guests [**RB**]

- Housekeeping before we start - make everyone aware of fire exit locations and toilets [**RB**]
- Restate the aim of the workshop - to participate in the evaluation of options for responding to global warming with the aim of producing a government policy brief [**RB**]
- Restate participants' ground rules for the day (e.g. respect for others' contributions; listen to what other people have to say; do not interrupt or criticise other people's points; punctuality to programme; take an active part; mobile phones on silent) [**RB**]
- Ice-breaker exercise - everyone to say their name and one interesting non-work thing about themselves. Specialists to be sat interspersed amongst citizens in the horseshoe [**ALL**]
- *MATERIALS: N/A*

20

10:10 - 10:30 Recap (plenary, led by **RB**)

- Recap what we did last time - we talked about options for responding to global warming and developed a set of criteria to evaluate them.
- We looked at these options in particular - low carbon living, offshore wind, carbon market, biochar, air capture, sulphate particles and business as usual. In addition to these, the ladies showed a lot of interest in evaluating an option of their own choosing - large-scale afforestation (planting trees) to suck up carbon dioxide. We have space for one more option in our evaluation - is there anything everyone feels should be evaluated that isn't here? Remember: it has to be something everyone is aware of and understands.
- The research team has gone away and analysed your criteria from last time and organised them into 7 overall criteria, relating to feasibility, effectiveness, cost, environmental impacts, safety, fairness and public views [**RB**]
- Hand out criteria sheets. You can see that within each of these 7 criteria there are a host of other 'sub-criteria' which help to define what we mean [**RB**]
- Today we are going to be scoring how well the options perform against your criteria [**RB**]
- Homework exercise - you went away and did some more research and used the website: what did you find out? [**RB**]
- *MATERIALS: 2 audio recorders, one with boundary microphone; spare batteries; criteria sheets*

45

10:30 - 11:15 Specialist fair

- We're very lucky to have two specialists here with us today. They are two of a number of specialists participating in this process to evaluate options for tackling global warming. I'm just going to introduce you briefly to the other specialists, so you can see who's involved [**RB**]
- PowerPoint presentation of other specialists in the process [**RB**]
- Now, with Matt and Jon and myself, we are now going to have a go at something a bit like speed dating! Matt and Jon will be sat at one table each, and myself at another. What we want you to do is to split into 3 groups of 4-5, and have one group sit at each of the

three tables - with either Specialist E or Specialist F or myself. We'll rotate every 12 minutes so you get to sit at each of the three tables. Whilst you are sat at each table we want you to ask questions and find out anything you think might help you evaluate the options for tackling global warming against your criteria (detailed on the handout). Matt sand Jon have their specialism's and I will be doing my best to represent the views of those specialists not here today [**RB**]

- Notes to be taken on key questions asked and answers given at specialists' tables [**KP with Jon & RN with Matt**]
- Make sure audio recorders are on [**RB, KP, RN**]
- *MATERIALS: 3 audio recorders with boundary microphones; spare batteries; posters; 3 note pads*

15

<u>11:15 - 11:30 Specialist fair review</u>

- Reconvene in the horseshoe [**RB**]
- Make sure audio recorders are on [**RB, KP, RN**]
- Ask citizens what they found out and learned; ask specialists for any further comments [**RB**]
- Lunch will now be served and the specialists will depart. Invite everyone to thank the specialists for their time and contributions [**RB**]
- *MATERIALS: 2 audio recorders, one with boundary microphone; spare batteries*

<u>11:30 - 12:15 Lunch</u>

- Lunch served [**Catering Direct**]
- Specialists depart - ensure smooth departure arrangements [**RB**]
- Participants to view posters [**ALL**]
- *MATERIALS: N/A*

90

<u>12:15 - 13:45 Scoring the options - session 1 (♂ facilitated by **RB**; ♀ facilitated by **KP**, supported by **RN**)</u>

- Everyone to reconvene in the horseshoe for plenary (allow 15 minutes) [**RB**]
- Introduce the task. We have seen the options, we have developed a set of criteria to evaluate them against. Now we're going to evaluate them, by giving them scores relative to one another [**RB**]
- PowerPoint presentation example. You will each receive your own scoring sheet for each criteria, which lists all the options we're going to evaluate. For example, one criteria is 'How likely is it that the option will be feasible?' Individually we want you to mark an 'X' somewhere along this line to show your view as to how likely it is. For instance, if you think that low carbon living is 'unlikely' to be feasible, place your 'X' here. If you think that it could be 'unlikely' but at the same time think it could equally be 'likely', place 2 'X's

to show your range of views. We want you to do this for each option, under each criteria [**RB**]

- Ensure all participants understand this task [**RB**]

- Break out into male and female groups (allow 20 minutes for each criteria cycle) [**ALL**]
- Distribute the individual scoring sheets for the 1st criteria: how likely is it that the option will reduce global warming? Describe the sub-criteria to clarify what it is they are scoring against. Participants to write names on top of each individual criteria sheet as they come to them. Fill out option 9 space if additional option had been chosen earlier. Explain that the unnamed one at the bottom is for any individual option you want to evaluate yourself [**RB & KP**]
- Individually, in silence, participants to score the options against the criteria by marking 'X's (allow 10 minutes) [**RB & KP**]
- Once individual appraisals are complete, the criteria poster is unveiled. Explain that we want them to transfer their individual scores to the same place on group poster using their unique sticky dots (allow 5 minutes) [**RB & KP**]
- Unique sticky dots - each participant has been allocated a specific set of sticky dots so we can trace back who did what. Participants must use their own sticky dots [**RN**]
- Once individual scores have been transferred, observe interesting scores and invite participants to explain their reasoning for those scores - in particular, high scores, low scores, those with big ranges, clusters, big differences, disagreements (allow 10 minutes). Invite participants to re-position scores if they wish, by removing their old sticker and adding a new one. Make a note of why this has changed [**RB, KP, RN**]
- Repeat with at least the 2nd and 3rd criteria (how likely is it the option will be feasible?; how likely is it the option will be affordable?)

<u>13:45 - 14:00 Break, everyone encourage to go outside and get fresh air</u>

- Tea and coffee and cookies served [**Catering Direct**]

🔊 [60]

<u>14:00 - 15:00 Scoring the options - session 2 (♂ facilitated by **RB**; ♀ facilitated by **KP**, supported by **RN**)</u>

- Repeat with at least the 4th, 5th, 6th and 7th criteria (how likely is it the option will have negative impacts on the environment?; how likely is it the option will have negative impacts on people?; how likely is it that the option will be fair?; how likely is it that the option will be acceptable to the public?) [**RB, KP, RN**]

<u>15:00 - 15:15 Break</u>

- *MATERIALS: N/A*

15:15 - 15:30 Weighting the criteria (plenary, led by **RB**)

- Explain that we need to express how important each criterion is. We need to give a 'weight' to each criterion. Each participant to individually distribute 20 sticky dots against the criteria on sheets, which will later be translated into percentages and the mean average taken [**RB**]

15:30 - 15:45 Process evaluation (plenary, led by **RB**)

- Invite participants to reflect on the process – on sticky notes please write down 1) what did you like about the process? 2) What did you dislike about the process? 3) What would you change about the process and why? 4) What have you gained/learned from the process? 5) Any other comments. Attach sticky notes to flip chart at front of room.

15:45 - 16:00 Close (plenary, led by **RB**)

- Thank participants for their participation
- The next steps: we will go away and analyse the data – would you like to see the results, we might do a prize draw for online discussion of the results?
- Hand out £100 M&S gift cards to each participant. Sign off each participant to evidence their receipt [**KP**]
- Distribute travel expense claim forms and stamped addressed envelopes - iterate that it essential they be completed carefully and clearly! We cannot reimburse if we cannot read! [**RB & RN**]

After the workshop

- Pack everything up (**RB, NP, RN**)
- Back up all data (**RB**)

Appendix 1.3.5 Citizen Scoring Sheet (example)

Name

How likely is it that the option will be affordable?

Mark an 'X' somewhere along each of the lines to show your view. If you feel that the likelihood could vary, show a range by marking two 'X's along the line. If you don't feel you can make a judgement on a particular option, leave it blank.

Option #1 - Low carbon living

Very unlikely — Unlikely — About as likely as not — Likely — Very likely

Option #2 - Offshore wind

Very unlikely — Unlikely — About as likely as not — Likely — Very likely

Option #3 - Carbon market

Very unlikely — Unlikely — About as likely as not — Likely — Very likely

Option #4 - Biochar

Very unlikely — Unlikely — About as likely as not — Likely — Very likely

Option #5 - Air capture

Very unlikely — Unlikely — About as likely as not — Likely — Very likely

Option #6 - Sulphate particles

Very unlikely — Unlikely — About as likely as not — Likely — Very likely

Option #7 - Business as usual

Very unlikely — Unlikely — About as likely as not — Likely — Very likely

Option #8 - Afforestation

Very unlikely — Unlikely — About as likely as not — Likely — Very likely

Option #9 -

Very unlikely — Unlikely — About as likely as not — Likely — Very likely

Very unlikely — Unlikely — About as likely as not — Likely — Very likely

Appendix 2 Results

Appendix 2.1 Example Transcripts

Appendix 2.1.1 Specialist Interview Transcript (Specialist E)

00:00 Audio recording begins

Researcher: Ok, so we might include cloud brightening because of the red team / blue team thing?

Specialist E: Exactly…

00:43 Criteria development begins

Specialist E: I guess you would have economic cost… I don't think economic cost should drive the decision but it will have a role to play… And then I would add lead-time, I think is pretty important… I mean if we decided we were going to do it tomorrow, how long would it-. Because space mirrors would take years to develop whereas if you were stupid enough to put sulphate aerosols in the stratosphere, you could do it tomorrow. But that's different from response time, which is the amount of time once you start doing it, it takes to respond. So I would have response time as number three… So lead time is basically technological development time, whereas… response time is if you decided to do it full scale, how long would it take for the climate to react. And then I would have safety… likely impact… in terms of risk to population and infrastructure… The argument that's always made is that CDR is safer than SRM. Efficacy would be my next one… Somewhere along the Royal Society's effectiveness. These things aren't all necessarily mutually exclusive.

Researcher: Do you mean radiative forcing potential?

Specialist E: No, it's really the relationship between-. Well, yeah I suppose. It's really about the relationship between the scale of what you'd have to do and the scale of the response. So, for example, some people think if you fertilise the entire of the ocean, you still wouldn't have enough draw down in order to have any significant effect. So it's how effective it is at a particular scale. It's always said that the cheapest, quickest and most effective thing you could do is the SRM, particularly the stratospheric aerosols; but also it's probably the riskiest. In terms of efficacy I'm thinking about how effectively and, at a suitable scale, you could reduce temperature. You could put it in terms of temperature reduction, though I'm not sure temperature is the right metric to be deciding these things… I guess I'd like palatability… How publically acceptable it would be, I think that's an important metric. How palatable it is. And I guess the last one; we can wrap it up in terms of-. In efficacy if you add how complete a solution it is, so one of the observations of SRM is that it doesn't deal with ocean acidification… Completeness of addressing the suite of problems.

9:00 Option scoring criteria #1 begins

Specialist E: I don't have a good answer. I know that a lot of nonsense is spouted about low carbon living. So David MacKay, Chief Scientific Adviser to DECC, he wrote a book about mitigating climate change. He pointed out that if the average household turns all of its standby electricity off for a year; that saves about as much energy as doing a six-minute car journey. So it's an observation that Boris Johnson has trumped with some monumental effort to get London to turn the lights off, but actually in the grand scheme of things, although it's quite a symbolic gesture, it makes very little difference. If you had one day where there were no taxis in London, you add a lot more in terms of ameliorating energy use. So I imagine it can be quite cheap, it's not a particularly difficult thing to do. So best case, I'd say 9, and probably worst case probably 5. There probably are some hidden costs, in going to a proper low carbon economy. So, for example, public transport is exceptionally expensive. So if you wanted to live a low carbon life you'd have to consider how you'd move yourself around…

Researcher: Offshore wind?

Specialist E: It is rather expensive, so I would certainly think it's more expensive than voluntary low carbon living… I would think that a low bound would be, there's not so much you can achieve with it I don't think, so minimum a 3, and a maximum a 6… So new market mechanism. I guess my logic here is that it's been tried and hasn't been particularly effective, so I understand it's a carbon credits idea but it just seems like… similar to derivatives in the financial market, they don't actually exist anywhere. They're just trading imaginary stuff, which seems to have got us into trouble in other things. So I'd say my faith in the working is even lower than for offshore wind. I'd put 1 and 3… Because it doesn't seem like a very… long term solution, it's essentially a licence to pollute, and so… I'm not convinced that the cost should be the primary driver, and so I can think of a situation where this might cause some environmental damage and I pay for it, that's ok. I'm not convinced it's a very good idea, and I think that the problem with Kyoto is that carbon is too cheap. And if you were going to do it properly it would probably be prohibitively expensive. So I forget what one tonne of carbon costs in terms of carbon trading, but it's not enough. Most experts agree is chronically undervalued…

Researcher: How about biochar?

Specialist E: I think biochar has some legs. In terms of efficacy I don't think it's the complete solution, but it's not necessarily particularly expensive. It's hard to imagine it being done on the necessary scale, but from what it does I'd say put it somewhere between 6 and 8. So air capture and storage is one that's really interesting, and I have quite negative feelings about it. In that it's not clear to me that anybody's thought about where you're going to put all your extracted carbon. And I think that will probably end up being expense, especially given the fact that the machinery which you use is incredibly expensive too. So I'm going to put that down the lower end, it's probably not as bad as the new market mechanism, but let's say between 2 and 5. I mean people like David Keith might find a way to make it really cheap and efficient, but I doubt it actually.

Researcher: And stratospheric aerosol injection?

Specialist E: Well it's terrifyingly good value for money. I mean that's not a good thing but it is. Ten million cubic metres of SO_2 into the stratosphere, without any consideration of its safety, just on a purely technological delivery basis is probably on the order of around a billion dollars. So if it gets to the point where Richard Branson… or Bill Gates, if one of those could do it themselves, it's terrifyingly cheap. So it's important for this one actually that low cost doesn't mean exclusively good, so it being really cheap is a slightly terrifying prospect… In terms of pure cost, cost as a driver, I'd have it between 8 and 10.

Researcher: Business as usual?

Specialist E: It depends on whether you're trying to capture the cost of doing nothing, or whether you're trying to capture the cost of what happens if you do nothing. Simply doing nothing is very cheap, you'd have to give that 9 and 10. But if you're talking about long-term societal costs, when you have to build more flood defences, build more air conditioners, the cost is probably quite high. But in terms of just literally how much it would cost to do that, it's one of the cheapest options we have… They're very high, they're trillions of dollars. So if your assuming that there's a cost down the line to pay, it's somewhere between 0 and 2, it's incredibly expensive.

Researcher: Cloud albedo enhancement?

Specialist E: It's pretty cheap. It's probably slightly-. Actually I don't know. I'd put it the same as stratospheric aerosols, so between 8 and 10… Because the delivery mechanisms, although different, are on order of the same cost. So these rather fancy looing boats that seem to be ubiquitous when people talk about marine cloud albedo enhancement. These things are self-driven, solar powered. It takes some designing, but actually once you've got them up and running, again the costs globally would be terrifyingly cheap… Much less than the perceived costs of climate change.

20:12 Option scoring criteria #2 begins

Specialist E: Technological lead times are slightly terrifying as well, so if you could be altering cloud structure in two years, that's not a good justification for doing it. It's just an interesting metric because it rules out-. If it takes us one hundred years to get to a point to remove carbon dioxide from the atmosphere using David Keith's technology, then we don't have a hundred years. So in terms of voluntary low carbon living. Hypothetically the lead time is really short, we could all just decide to stand up tomorrow and say right, fine we'll turn everything off, we'll use our cars less, we'll fly less, we'll take holidays in the UK, we'll eat local food etc. But practically people have known about this problem for a while and it's not really changing behaviour. So I would actually think engendering social change on that order would need a rather long time scale. So I guess I would put the lower bound at maybe 1, but the higher bound is actually quite high… So the question becomes how fast is that likely to happen? You might see behaviour change as a function of the heat wave that's currently going on. People buy into the fact that it might be caused by climate change. If they do then they might change their behaviour really fast, so I'm going to give the upper bound an 8… I can imagine a situation where it gets so serious that people suddenly start to realise they need to change their behaviour.

Researcher: What about offshore wind?

Specialist E: Offshore wind has a relatively short lead time, we're already doing it and DECC has just sponsored a load more I see… So I would put a lower bound of 7, upper bound 8. I'm pretty certain they have a short lead time.

Researcher: What about the new market mechanism?

Specialist E: I'd say this would take quite a lot longer. If you want to slow something down, try to get economists to come up with a global strategy. So probably somewhere between 2 and 5, I'm not so certain about that, but I imagine the lead time would be relatively quick. Biochar, it's hard to know. In principle you could start doing it tomorrow, but to get it to the sort of scale that matters would take a long time. But I'd be betting on that acting faster than a new market mechanism, so let's say 5 and 7. Air capture and storage I think has quite a long lead time, I don't think we're anywhere near the level we need to be in terms of technological understanding, so I'd say 2 to 4. Despite what other people think, actually stratospheric aerosol injection is not a particularly well understood fora either. And so I would think that we're nowhere near as advanced, in terms of technology, as we are with something like offshore wind energy. Some people think we could be doing it in two to three years, but I think that doesn't capture the uncertainties that we'd have to overcome in terms of understanding what happens to the climate if we did it… Actually deployment is more like 20 to 30 years. So I would put that somewhere in the middle, so 4 to 6. I think it is demonstrably faster than air capture, and probably on the same order as biochar.

Researcher: Do you think the SPICE stuff, what happened with SPICE, will have a bearing on the lead time?

Specialist E: Potentially, I think it might slow the technological development down a little bit. And that, in most people who do climate engineering research's minds', is a good thing. A lot of people are quite uncomfortable with the new developed technology; they think it's a bit ahead of the curve. So I imagine in terms of necessary full scale development it won't make that much difference. But in terms of making the technology ready it'll probably make a considerable difference. There is this argument about, why develop the technology if you don't know if it's ever going to be used… I think if you ask different people you get very different answers. So the engineers just spin it round and say, it may not be technically possible to inject sulphur into the stratosphere this way, so you're wasting your time worrying about the chemical effects, when we can tell you quite quickly what you can do. So it becomes less of a technical answer and more of a perceptions answer. So people were comfortable with people in a lab, people with a computer, doing careful, non-invasive, quiet, inside work; but as soon as you get outside, even with something as benign as the SPICE test bed, and say actually, no this is going to be highly visible, it's outdoors, we had to be thinking about this stuff that throws up a lot of opposition. That part of SPICE is essentially a lightning rod for people that don't like it as an idea, and it's one in a number of battles that'll happen over the next five years until somebody decides to do an outdoor geoengineering experiment, and call it that. There have been some that are demonstrably geoengineering based already, either that just weren't mentioned until after the experiment was conducted, which is a bit naughty, or they were badged as something else… The iron fertilisation thing did have a problem because people realised. But there's this thing called E-PEACE, which is this cloud-seeding experiment, on the west coast of the US, it is basically cloud microphysics, but it will tell us a lot about whether cloud seeding and geoengineering will work, that aspect will work. And they are now the focus of a lot of people's attention because they weren't particularly up front about it, that aspect about it beforehand…

Researcher: How about business as usual?

Specialist E: Business as usual has a lead time of 0, right, so that has to be 10 and 10. I'm not sure whether all of these will work. Cloud albedo enhancement probably has a similar lead time to SPICE, possibly shorter, so I'd say it's more in tune with biochar so maybe 5 and 7 rather than 4 and 6… Because we're a little bit further along in terms of where the technology is and I don't think it's quite as difficult to challenge. It's easier to deploy particles at 1km than at 20km by definition, so I think that makes it more likely to happen. Well, it gives it a shorter lead time I don't know if it makes it more likely to happen… You can begin to do it tomorrow if you wanted to; in fact E-PEACE has already done it. On the sort scale you'd need to do it in order to make it effective it could take a while, but in terms of experimentation they're a bit further along.

30:04 Option scoring criteria #3 begins

Specialist E: I think in terms of low carbon living it would potentially take quite a long time, and that's really a chemist's answer because you've got so much CO_2 in the atmosphere even if you-. This is not quite true but if even you stopped using carbon dioxide at any sort of scale tomorrow, according to my experts, and I don't count myself amongst those, you'd probably not quite get to 2 degrees of warming, you'd get close, but actually we'd be under 2 degrees of warming. But given how long it's likely to take in order to move to a low carbon economy and voluntary low carbon living, I think we are therefore committed to rather a lot more than 2 degrees. So depressingly the half-life of carbon dioxide is going to solely dictate the response time, and that's on the order of hundreds of years. So it's long, I'd put it somewhere between 1 and 3. Offshore wind energy does have the capacity to make a difference on a slightly shorter lead time, particularly in terms of energy, electricity development. Electricity is obviously not the whole story, but actually in terms of reducing our need for carbon directly it has quite a short lead time, plus the fact that it's already happening, so I'd put it somewhere between 6 and 9. The only reason I'm not giving it 10 is because I don't think it makes much difference at the moment. When it starts to come online, it will. I don't think it's particularly effective at the moment in terms of the number you'd need. Somebody worked out you'd need something like five large offshore windmills to power one Virgin Atlantic train, something like that… New market mechanism, I have very little faith in it ever working. I'd suggest the lead time would be somewhere analogous to low carbon living. In fact, I could imagine it never making a difference so 0 and probably 3. Biochar could make a difference but probably not on the scale that you need it to… So I'll put them between 5 and 7 because it is technically feasible to do rather quickly… [Air capture and storage], that's incredibly long as well, it's shorter than voluntary low carbon living, I think, but not by much, so 2 and 4. Because you're not solely reliant on the lifetime of carbon, because you've got negative emissions technology. Stratospheric aerosol injection, incredibly fast, terrifyingly fast, so once it's deployed on the order of 9 to 10. It's really rapid. If you pump sulphate aerosol into the climate, a month later it'll be cooling… Certainly in six months, it'll be colder quickly. If you look at Pinatubo's response it's on an order of months. Business as usual… it wouldn't ever make any difference so that'd be a 0 and a 0.

Researcher: What about cloud albedo enhancement?

Specialist E: Cloud albedo enhancement is also pretty quick, it's probably not as quick globally as stratospheric aerosols but certainly it's up there so 8 and 9… Because the point about global cooling in terms of stratospheric aerosols is that you can put an aerosol layer everywhere; whereas there are only certain places at certain times of the year that you can enhance clouds without having a warming effect. So the piecemeal approach you'd have to take would mean it would take longer… But it's still quite fast.

35:57 Option scoring criteria #4 begins

Specialist E: Voluntary low carbon living is ultra-low risk so definitely 10 as a maximum… Probably put 10 and 10 in there, because it certainly seems like a sensible thing to be doing anyway. Offshore wind energy I'd say 9 and 10, there are some issues around. Bird strikes and things. Whether or not you can have them everywhere and how you'd have to then move the energy around in the grid would cause some sort of environmental discomfort but it would be very minor. New market mechanism I suppose is also pretty low risk, but… I suppose it's also very low risk so let's say 8 and, at its best it could work very well, so 8 and 10. Biochar is a little bit more risky because you have issues around what you do with your waste carbon… You have to burn the stuff in order to capture the carbon in charcoal, but in burning it you're bound to release CO_2, so you have to work hard… I'm not particularly expert in this, but it's not clear to me that that process is particularly efficient. And so you can't release it into the atmosphere, otherwise that's basically setting fire to forests which is stupid. So if you capture the CO_2 somehow and then what you do with that CO_2 has some potential impact. And when you combine it with afforestation actually it's probably pretty benign, but it's not completely benign so I'd say maybe 6 and 8.

Researcher: What about air capture and storage?

Specialist E: It's relatively low risk. It does deal with the root cause as well, which is quite attractive. But it's basically in my mind, not that different from biochar. It's probably slightly safer because you don't have this risk of handling your waste carbon-. They're probably similar actually; let's say the same, 6 and 8… I haven't the expertise to be able to differentiate between the two… I don't think stratospheric aerosol injection is particularly safe at all, so I'd say 2 to 4… Because it will demonstrably have an impact. In my mind it's an emergency measure. But it's quite clear actually that lots of things change after things like the Pinatubo eruption, so weather patterns change, there's less rainfall in the tropics, plants respond differently to lower light levels, so it's not a free ride, it's not a perfect solution it's a band aid. I don't think it will ever be particularly safe. I mean you could make the argument that Pinatubo erupted and nobody was-. There was a profound impact globally on society but if that eruption had continued for years… I'm thinking of things like, it's very clear that there some very sensitive large-scale weather systems, particularly the Indian monsoon and the rainfall in sub-Saharan Africa that are quite sensitive to the radiative balance of the Earth so people have postulated that you should flood the Northern hemisphere with sulphate in order to protect the Arctic, but recent research has shown that all that does is pull the ITCZ down toward the South Pole. And what that does is it takes the air that is normally maintaining the desert by very warm dry air and pull it down over the Sahel and reduces the Sahel's capacity to produce any sort of agriculture or sustain life. You would have a situation like you had in the 1980's with sub-Saharan Africa. Every year would be appallingly bad for hundreds of millions of people

Researcher: What about business as usual?

Specialist E: Demonstrably exceptionally risky, so I would say… 1 to…4. I'm not that much of a sceptic. So this is the whole point about SPICE, is that SPICE might make things, life better or not. The reason I haven't gone to 5 is that I can't imagine climate change ever being less serious than injection, just based on the limited knowledge that I have… So do I ever think there's a situation where the effects of geoengineering might be more serious than doing nothing? No, I'll leave it as it is. My suspicion is that geoengineering might cause us different problems but my instinct is that they won't be as severe as business as usual. I think business as usual is actually really serious. If business as usual was more like actually starting to behave ourselves on a longer timescale, this number would have to come out. But ploughing on business as usual I think is never going to be a better option than geoengineering.

Researcher: What about cloud albedo enhancement?

Specialist E: This one's interesting. I was very dismayed by an article by John Vidal in the Guardian, who basically said that stratospheric aerosols were bonkers but cloud albedo particles was pretty harmless I think is what he said. And that's absolute nonsense; it's in the same risk category as stratospheric aerosols in the Royal Society report for a reason. So the thing about albedo enhancement is that more can go wrong, but you can turn it off faster if it does go wrong. The point about cloud albedo enhancement is that you make lots of small particles, but if those particles grow, or you don't make them right or they bump into one another and you get big particles, the you have exactly the opposite effect and I think that's a massive risk actually. So I'll say 3 to 4… I think it's marginally more safe because I believe, although there are some questions around this, but I believe John Latham when he said if you didn't like it you could stop it and you wouldn't feel the effects more than a few days. I'm not completely sure that's true, but I know that the lifetime of aerosols in the troposphere is a lot shorter than those in the stratosphere… You run the risk of moving rainfall patterns around which is the thing I really objected to in John Vidal's article. Clouds are one of the mechanisms where you move the most precious resource on Earth around, and if you monkey with that, if you have unforeseen consequences that would be exceptionally dangerous. I suppose there is this concern that you can't make it, because you're spraying stuff that makes cloud condensation nuclei, or act as cloud condensation nuclei, I'm not sure how far down the stream you can control particle size of the thing you're making. It's slightly easier with stratospheric aerosols because you could inject something where you could probably control the particle size quite well. Although there's another question about whether that would be good for atmospheric chemistry… Effectively that reflects my binary view that soft, painless, but probably not particularly effective carbon management strategies, and then bonkers business as usual and SRM is into a different category.

47:57 Option scoring criteria #5 begins

Specialist E: Now I think I'll be completely reversed, because I don't think any of the top five are particularly efficient or effective. So voluntary low carbon living, if it happened could be quite effective, but it's not going to happen, so I'm going to put that at between 1 and 3. I did get a very amusing letter from, amusing's maybe not the right word, an old lady who lives in London, who's quite famous where she lives, for having a zero-carbon footprint. She told me I was a nutter and she said a perfectly simple answer, just don't have a carbon footprint like me. It's hard to argue with, she doesn't get in her car, she doesn't heat or have any light in her house and she doesn't cook any food… She's lives a miserable energy free existence but she lives. She's incredibly fit, she's 70 odd and she runs several miles a day, she eats all raw vegetables. I have to say, for the record, I have a tremendous amount of respect for her, but her solution is not practical at a population scale. If we convince everyone in the population to live like her we would not have a problem, but you won't. So it's not a particularly efficient solution. Offshore wind energy, a drop in the ocean, realistically. So David MacKay also said, this was for onshore wind but it's the same sort of numbers that terrify me, is that you'd have to cover, I forget what it was, three-quarters of the land's population in wind farms in order to completely sate the country's desire for energy. So you'd need something like four per square kilometre. So it's a partial solution. And the danger of your strategy actually is that you end up forcing people to choose between them but, and actually for the record, in general a broad portfolio of a lot of these is the best way forward. So I don't think offshore wind is that efficient, I mean it helps so 2 to 4. I have absolutely no faith whatsoever in new market mechanisms, I think they're utterly ineffective. It's worse than doing nothing, so 0. At its best it might be mildly efficient, so 2 tops… I just think it's a get-out-of-jail-free card. I think people will look at the price of carbon at the moment and because the framework is purely economic people will think it is easier and cheaper if we can burn the CO_2 and buy credits off somebody who doesn't have as large a carbon footprint rather than do the right thing. There doesn't seem to be any threshold or any consideration of latitude proximity elevation on where and how the carbon is produced. So it seems to me a very blunt tool that won't work very well. And will let a lot of rapidly developing nations off the hook. Biochar I think is great but is massively inefficient and ineffective. So I'd give that no more than 1 to 3 in terms of its efficiency. It's a 10% effect, that's the problem. You'd never get to the scale where you could use it aggressively on a global scale. I mean it could be part of the solution, but actually on its own it's relatively ineffective… Because there just isn't the numbers. You'd have to burn monumental amounts of wood, and you'd then have to deal with the inefficiency of the burning process and capture all that carbon. Yes, I know it's a good fertiliser and I understand why biochar will work on a small scale, but actually you'd have to sacrifice huge swathes of the land surface to do it on any decent scale. There just isn't the land available. If you do the sums, it doesn't ever end up being more than a few per cent.

Researcher: What about air capture?

Specialist E: So there's a timescale issue here. In the long term it might be rather efficient, but in the short term it falls under the same problems as biochar. So I would say it has the capacity to be more effective but at the moment it's probably less so 1 to 4… Because we don't understand how efficient might ever become. And so I can imagine the situation where carbon dioxide removal by person / fridge-sized systems… where every house could have one of those. And actually that would be much easier to do than everybody doing biochar. And I think that pound for pound that process will become more efficient than biochar. Biochar has some physical chemical limits as to how much carbon you can lock up in the system. Whereas in terms of the technology, if you get really efficient at pulling CO_2 out of the atmosphere, one of these little devices might actually make a considerable amount of difference, or lots of them might make a considerable amount of difference. But that's a long way off.

Researcher: What about stratospheric aerosol injection?

Specialist E: It's quite effective but it doesn't address ocean acidification, so I would say 7 to 8. I can't give it any more than that because it doesn't deal with the ocean, it doesn't deal with coral bleaching… It's very easy actually, alarmingly easy, to see a reduction in global temperature that you want. It's hard to get the balance between the poles and tropics right, but actually if you wanted an average cooling of a degree you could do it. The question would then be, because the Arctic is warming so fast, you'd probably undercool the Arctic and have to overcool the tropics in order to get the same effect. On an average temperature metric, which would contain some problems with stratospheric dynamics, but it's really the effect that would have on rainfall. The problem with stratospheric aerosols and other SRM is you can't ever get back to what you want; you're just taking a slightly less bad path, if you like. But the idea that you could pump this stuff up there carefully and you'd end up creating pre-industrial conditions is absolute pie-in-the-sky.

Researcher: What about business as usual?

Specialist E: It's no solution whatsoever so it should be just 0 and 0.

Researcher: And cloud albedo enhancement?

Specialist E: I think it has the capacity to be as good as stratospheric aerosol injection, but I don't know it well enough so, I'd say 6 and 8. I'm prepared to admit it may become as effective; it has the capacity to be as effective as sulphate aerosols, particularly on a regional basis. But actually at the moment I don't think it's quite the same… So my perception is that carbon management strategies are slow, safe and SRM is fast and dangerous, but effective. That's exactly how I do feel.

56:51 Option scoring criteria #6 begins

Specialist E: In terms of low carbon living I think it's probably moderately acceptable, as long as it doesn't dramatically impinge on them. People are just lazy and don't see the scale of importance. But actually there will come a point where you start to impinge on people's lifestyles, so I think it would have been really fun, and I think this would stress a lot of people out… How many of them would have given up their mobile phone?... People are quite happy doing low impact stuff but something that really matters like not driving, not spending all your time using energy hungry equipment, and we've got used to that. It's very difficult to undo that. Any suggestion the public has to be returned to what the cynics call 'the stone age' in the narrative is always met with derision. We have to move forward, we have to get better and more efficient. Where if you start impinging on people's lifestyles, even the stuff that most would accept is not necessary… It's pretty acceptable, so I would say probably 5 and, if I'm being really optimistic 8. There comes a point as when it becomes more and more effective and more and more difficult, people don't like it… Offshore wind energy, it's not hugely publically acceptable, especially with Donald Trump. So his golf course's view has been ruined by some offshore wind farm… He's kicked up a massive fuss... Offshore wind energy, I think that's pretty acceptable actually because there's this out-of-sight, out-of-mind thing. I mean not everybody is enamoured with offshore wind energy, but I'd say probably somewhere between 6 and 8. New market mechanism, I can't work out whether everyone is as cynical as I am about it. But given the financial backdrop and that all of these people seem not able to either have or respond to a strong moral compass, I suggest this stuff looks like smoke and mirrors to me. My intuition is that it'll be less acceptable than the other stuff, so 3 to 5. Does it become another LIBOR? Biochar, I think that's probably pretty acceptable. It sort of feels quite soft, and it's often combined with fertilisation and afforestation which people always like, so I would think that's at the high end, so probably 6 to maybe a 9. Some people don't see the downside of it; it's not immediately obvious I guess. Air capture and storage, is also relatively popular with the public I think. Probably not that popular, because there's a difference of naturalness between these two, so I'll bump it one in each direction so 5 and 8. Because air capture and storage looks like a machine, and biochar looks like nature, especially when you do grow things on the stuff that you've burned. Stratospheric aerosol injection rightly scares the [EXPLETIVE] out of everybody, which actually I don't think is a bad thing at all. But it's not particularly acceptable. In terms of deployment it's probably somewhere between

1 and 3 I think… I don't think they like the idea of these balloons and hosepipes. I think they think they're very dangerous and science-fiction. They symbolise control and departure from nature and playing God and all the rest of it. And there's no nice way of saying we're going to spray ten millions tonnes of sulphuric acid into the stratosphere… You can kind of dress it up but actually when it comes down to it, anybody that understands it, it'll be the single most obvious sign of our failure as a species to act as global stewards. It's an admission of failure, under duress. I think the only way it'll ever be used is in an emergency where we really haven't behaved when we should have been, and even then it'll be risky. And I think the public know that, recent reports suggest that if you ask the population how they feel about research and deployment, 75% of people think that research is a good idea and 25% don't like it. It's exactly the opposite for deployment... I feel exactly the same actually. I think people are, I think David Keith pointed out, their initial reaction is one of revulsion and alarm, but I think that's ok.

Researcher: Did you personally experience any of these attitudes during SPICE?

Specialist E: I've had the odd nutter email me, a proper nutter emailed me. Most of the stuff they say is unintelligible. I've had a few people, very sensible people, say this is very scary it doesn't seem like a good idea. So I took the time to write back and say, look here's what we're doing, it is very scary but actually it's the beginnings of it. So short term, are we in a CERN-like, mini-black hole ending the world next Friday situation? Absolutely not, but actually the ramifications of even having to think about this are serious. And so I had… a handful of people emailing me saying they don't like the sound of this at all. But when they were approached they were much more understanding, once they understood what we were doing rather than what it sounded like we were doing they were pretty supportive. There are people who absolutely detest it, and that's fine. They're absolutely entitled to their opinion. This stuff shouldn't be easy and it shouldn't happen quickly. And they'll be responsible for slowing it down and asking difficult questions which is good.

Researcher: What about business as usual?

Specialist E: It's quite high; I think it's higher than it should be. I think some people just think it'll be alright, it's not really real, it's so far away I don't really care, scientists will get us out of it… It's interesting that the same scientists are saying we're completely screwed… I think business as usual is much more acceptable than it should be, so I'm going to put it at between 3 and 7. Some people don't accept the fact that it's absolutely unacceptable. A lot of people are trundling through life thinking we'll be alright. I suspect they feel much better about cloud albedo enhancement than they do about stratospheric aerosol injection, because scary balloons with acid are one thing, but little fluffy clouds is something else. Despite the fact that they're not that dissimilar in terms of risk. So I'd say that's fairly palatable, I bet that's 5 to 8, although I could be wrong.

01:08:12 Additional option scoring begins

Specialist E: I'll give you two freebees, I'll give you… Space reflectors I'd like to, I could approach… And I'll do afforestation because I think that's really interesting… [Space reflectors] is so unlikely. It's never going to happen. It's stupidly expensive and much riskier than people realise. But it's the one that everybody talks about…

Researcher: On economic cost, how do space reflectors perform?

MW: It's bonkers expensive, it's incredibly expensive. So given that expensive is bad, it's between 0 and 1. And actually afforestation is incredible cheap, so it's probably 7 to 9…

Researcher: And lead time for space reflectors?

Specialist E: It's quite long, so probably on order of, definitely longer than stratospheric injection, so let's say 1 to 2. And afforestation the lead time is 10, you don't need any lead time, people are doing it now. The Chinese have shown on a massive scale it can be done very quickly.

Researcher: And response time?

Specialist E: The response time for space mirrors is incredible fast, so it's probably between 9 and 10. It's analogous to stratospheric injection. Afforestation is much slower, so 1 to 4. There's some uncertainty in where and what species of plant you plant… So each species has a variable uptake rate and there is some suggestion that you're better… of doing it in the tropics rather than in the high latitudes. So a lot of the stuff that's planted at the high latitudes doesn't get you very far in terms of CO2 reduction… It may be the other way round…

Researcher: What about safety?

Specialist E: Space mirrors aren't that safe, you could turn them off faster than you could-. So probably on order of cloud albedo enhancement. No, maybe a bit safer than that, so 4 to 5… If you stopped, if Obama or whoever it was who had the button, just said stop doing that, if you stopped pumping sulphate into the atmosphere it'd be there for around six months probably in decent quantities. Your tropospheric cloud brightening aerosols would be out for a few days or a few weeks, no more than that. But, in theory, you could switch your space mirrors on order of hours, so it should be really fast… It comes with the same problem that the other things come with. In that it may be very efficient at reducing the amount of radiation against the Earth's surface, but what that does to stratospheric circulation, rainfall, large-scale weather patterns isn't really clear. So you could perfectly reduce the Earth's temperature to zero change since 1990, but that might turn off the Asian Monsoon. You cool the planet, but put a billion people under water stress…

Researcher: And what about afforestation?

Specialist E: Incredibly safe, somewhere between 9 and 10… There are some risks but they're pretty low… I'm thinking about risks to things like biodiversity, so you may show that one particular type of Pine is the best, I mean I don't know anything about the speciation you'd need, but if you suddenly decided to plant a huge swathe of very similar plants that would have impacts on biodiversity and things like disease… I guess it more represents my uncertainty in how you would go about a massive afforestation programme… Afforestation is different to reforestation… You're actually aggressively going out and changing land cover, and it would also have an effect on things like food prices and food availability. And that comes with some manageable risks.

Researcher: What about efficacy?

Specialist E: Space mirrors are pretty effective in terms of temperature, but they don't-. They're probably the same as… It's very similar to SPICE so 7 to 8. Because it doesn't deal with ocean acidification. Afforestation is wonderful but will struggle to have a difference in our lifetimes, so 2 to 4…

Researcher: Public acceptability?

Specialist E: The public acceptability of space mirrors is bonkers. But it's probably more acceptable than aerosol injection because of the element of control that you'd have over it… Let's say 3 to 5. These are pretty arbitrary numbers. Afforestation is universally probably 9 and 10, everybody thinks it's very safe, very logical. There are some issues with afforestation, but in general the public thinks it's the way forward.

01:23:55 Weighting begins

Specialist E: I think safety is critically important so I'll give that… Economic cost I don't think should be a driver but could easily rule stuff out… Economic cost is not zero, but actually I don't think is a particularly important driver. The lead time is important because if the development time is hundreds of years… The response time is important as well because we may have to do things really quickly, although I'd say it's not that important because the earlier we deploy things like CDR the less the response time matters. Safety is of critical importance, it's the thing that ought to decide whether we do it or not, coupled with its effectiveness. And public acceptability is important because it'd be very difficult and unethical to do it without public support.

Researcher: Why wasn't economic cost an important consideration?

Specialist E: Because making decisions based on economic cost is what got us into this mess into the first place… Arguments about we should do this because it's cheaper than what climate change will cost don't fill me with joy. So if you did the thing that was cheapest that wouldn't necessarily be the best…

01:33:00 Process evaluation begins

Specialist E: I think it works about as well as it can do. I think the problem with this is it's probably designed where, and maybe this is just a lack of understanding on my part, it has the effect if artificially forcing one to make decisions about a particular technology. One of the mantras that is often encountered in discussions of geoengineering is that there is not silver bullet, there may be a silver buckshot… People aren't yet conceiving what happens if you combine these. So for example… if you change the amount of light coming into the top of the atmosphere by loading it with sulphate aerosol, we don't know what that does to clouds and the way clouds are made. So there may be some connection between sulphate aerosols and cloud albedo enhancement that isn't well captured. So it's difficult, there's a lot of entrenchment going on. People getting labelled as advocates for particular types of geoengineering.

01:34:57 Audio recording ends

Appendix 2.1.2 Citizens Panel Transcript (Issue Framing Session, First Panel, Men's Group)

Researcher: When thinking about global environmental issues, what are the most important issues that come to mind?

P7: Population, overpopulation.

P4: Energy, requirements.

P2: I'd say energy as well.

P12: I'd go for population as well.

P4: Which are linked in aren't they? Yep. Obviously, food, water. It's all population related isn't it?

P11: I think most things are linked in some way or another.

P9: I think one of the main things that we've got to do for the future, starting as soon as possible, is to get the energy costs down. Because more and more elderly people are unable to afford the cost of electricity and gas and so on. So instead of producing these wind turbines which only supply a very small quantity of electricity, for a very high cost, we've got to think of a way to produce energy more cheaply so that it is affordable by everybody.

P5: I think things are bad enough that we have to look beyond cost. I think we're at the stage now where we have to identify and stop doing irreparable damage in lots and lots of areas. We really are. My ex is very much into green politics and has always had this thing about, well you don't want to make it seem too bad because there's no point in doing anything. But I think we're beyond that point now. People just really need to know just how bad it is. And also I think people want to be, need to be backed up on some of the evidence, because so many people think that politics and invested interests behind the climate concerns. It's not a lot of it. There's some, but most of it is hard science. 20 years ago there was a lecture at the UEA and they were flying a plane around the ozone hole and mapping the structure and why the hole was there. 20 years ago they didn't know why it was there. And he finished the lecture by saying the evidence is in, I'm afraid. Up until now the evidence has been speculative, the evidence is in. Climate change-.

P2: I still don't believe the scientists understand a lot of-. We've been around for such a small period of time, of the Earth's history-.

P5: But they can drill-. They drill down in Iceland, right, and they can tell exactly what elements are in the air and have been for the last 300,000 years by taking ice out. That's the sort of evidence we've had.

P2: But there's a difference between analysing what was in the air, and I agree that making our air cleaner is good thing to do. But saying that it's causing all the problems is not necessarily true.

P5: No I'm not saying that at all. What I'm saying is that's the sort of evidence that we're basing it on. We're not basing it on our-. We're basing it on solid science, and it's not just that. There's all sorts of, you know, all sorts of other evidence that's in. And when it-. And another big thing that's happened in the last 10 or 15 years is computer power. The climate models that they use, they basically try and make a model that shows what, with the data they put in, produces a climate like we have now. And for years they've had to, what they call parameterise, whole systems like clouds, so little is understood about clouds, they had to parameterise with a little figure thing. But as computing power gets higher and higher and higher, they're able to build the model in for the clouds and stuff like that. And when there's this big change, say 10 years ago when scientists stopped saying maybe, they're saying, well, actually, that was when they reached-. They're producing models that could not only work, they could run them backwards and it matched all the data from ice samples and things like that and magnetic samples in rocks. And they ran their models backwards and it fitted perfectly to the past. That gave them the confidence to run it forwards and say this is going to happen.

P7: But that's science-.

P5: But it's based on evidence, hard evidence.

P7: Yes, I know and it's always got to be evidence. There's always got to be ways of trying to predict how these things go forward. But it doesn't take account of people and what's likely to happen. With world population, with economies, with this thing going for growth at all costs, and the fact that no particular country out there is wanting to hold back on that. And even our own country, it's still all about growth. And growth is not sustainable. So the models are great, but nobody is doing anything to try and save the world. Everybody wants to use these limited resources to the point where they don't exist anymore. And then there's nothing left.

P5: You're absolutely right. I mean you said an important thing there, all that's... and you have to fold that back onto people. And tragically as individuals there's not a lot that we can do. We can choose to cycle and not to drive, and we can recycle our stuff. But these are really tiny things. Richard Branson's right when he says the solutions will come from industry.

P2: I think the problem is that humans aren't programmed to think long term, we're programmed to deal with our situation. We're programmed to deal with what do I need at the moment? I need food, I need work, I need this, that. Based on your needs. You're not trained to think 40 years down the line or even 200 years down the line. This is going to be a problem, because it doesn't concern you at this point in time.

P5: Indeed. I think everyone's duty as an intelligent human being is to break out of that programme and start-.

P12: I think... a lot of the problem is that politicians don't think long term. They can only see as far as the next election, and so that whatever decisions they make, have to be based on-.

P5: And tragically we've always been looking to them for answers.

P12: Yeah.

P5: Again, Branson makes it clear, it said we're looking in the wrong place.

P12: In this... we've got a maximum five year life of government and sometimes that's not long enough to achieve things. And if governments have to do unpopular things, they cannot do things that are necessary.

P7: What is Richard Branson's motive? It's to make money.

P5: That's fine, he's saying now that it actually pays to be ethical. He's saying, for instance, Coca Cola, brought in this man to clean up their act, and he's reduced their carbon footprint colossally... And made 400 million the process. And this has happened, GEC has turned the industry round, Coca Cola, loads of stuff. Branson's book is called Screw Business As Usual... the good side of this is that it now pays to be green. And they're big.

P9: We get all these models, but if you compare them with the fact that they can't produce the correct weather forecast for the next day, it makes you a bit sceptical.

P5: You're probably like me, you don't look at the weather forecast any more...

P9: I think also that if we take into account that the Earth has shifted on its axis twice quite recently, that has altered the perspective of the models that they have been producing.

P5: That's pretty ancient data, I mean if the axes shift that was so long ago that... the magnetic poles flip more often than that...

P9: The latest one was the Tsunami in Japan wasn't it? That shifted about half an inch? Moved the-. To what I read in one of the scientific journals.

P5: Yeah, don't read New Scientist, it's bad science...

P2: That's going to be your problem then. If scientists are contradicting each other, like there are still some that are against global warming I know this. And there are some that seem to pursue their own viewpoint. I seem to remember there was actually something at the UEA not too long ago, about someone wanting to remove some data because it didn't help their point of view.

P5: Whenever you-. You see this is-.

P2: That's the thing, when you hear things like that, when you have scientists going against each other.

P5: But they weren't, that's the thing. You're talking about what the media was saying. In fact what he did was he wrote some things that are perfectly valid statistical tools. You've heard about mean differences and standard deviations and things like that, he was just talking technically to his people about things like that. And anyone could interpret that and make the whole case that they did. In fact, you should have read the results after the investigation that said there was no wrong doing, no twisting of evidence. But the paper's didn't report that because that's not good-. They want, the media, people who work for Murdoch, making money, want you to believe that scientists are completely-. There are about 60 main climate sceptics on the planet. You can go through and I've shown that every one has major interests in the status quo. No real scientist, no honest scientist will deny global warming is-.

P7: Scientists don't rule the world anyway-.

P5: Tragically, no.

P7:... Are going to get ignored because of business interests... And from my mind, one of the biggest things are the emerging countries. And the voraciousness of eating up the planet's resources, and seemingly no controls over what they're doing…

Researcher: … What comes to mind when you think about global warming?

P9: David Bellamy comes to mind, and of course he doesn't agree with it. He thinks it's a load of tosh. But if you compare global warming as they call it today, when we came to the end of the ice age, it wasn't because there were factories churning out smoke from chimneys and motor cars going round because there was nobody on the planet. But it was a natural phenomenon that the ice melted and so we carried on from there. But it wasn't any contributory factor from the human point of view because there were no humans at that particular time. And I think that perhaps a very small part of global warming is now contributed by humans, but less than it was during the industrial revolution when of course there were lots of factories churning out smoke all over the country. But I think that we've moved on from that and we have scaled down. Now of course it's more traffic that's causing the pollution more than anything else.

P7: The melting of the ice caps and all the rest has got to be enough proof as anybody needs that it's happening-.

P5: And fast.

P7: Sea level's predicted to rise etc.

P5: Glaciers are retreating 20 times faster than 10 years ago.

P7: So I can't see that anybody can deny it's not happening… How serious it is, what can be done about it, all these things seem to be much more complex.

P5: Do you know how much the sea level rises if all the water trapped in ice above sea level melts…

P11: About 300ft isn't it?

P5: About 85 metres…

P12: You don't only have the volume of water of the ice because if the temperature rises then the water expands anyway in the oceans.

P5: Yeah there's that as well… There's a bit about to break off now and I think that's about a metre on its own. There's a shelf, there's satellite pictures, a crack down it and a little bit left… They're not quite sure how fast they've only just noticed it, but if that piece alone breaks off and melts it's something like a metre globally…

P12: I was just going to say that at the bottom of a lot of the problems are global commodity prices. They drive the way that resources are used. And one example that was, many years ago, when Mrs Thatcher was in power, before we worried about global warming, she closed the pits down for the coal mining industry, for political reasons.

P5: The tragedy is that someone said earlier on they came at the first Rio summit and sort of the one line conclusion is the trouble is, the basic trouble is population, and there's nothing we can do about that.

P12: If you look at, going back to the economics of that again, a lot of the electricity generator stations were converted to gas, North Sea gas. And the argument there was that the only cost of that gas was the extraction costs. So the economics of it were that it should be got out of the ground as fast as possible because the gas itself didn't cost anything… With me saying that gas belongs to me and my children and grandchildren. Not yours to use now. And to leave all that coal in the ground unused, inaccessible to future generations.

P11: I think a lot of the problem is that we don't get told the truth most of the time.

P5: You are so right.

P11: Large companies and governments, they're a load of lies, they keep telling us lies. To get the first nuclear power station's down we were all convinced that it was going to be so cheap we wouldn't get a bill because it'd be too expensive to send it in the post.

P5: Too cheap to meter.

P11: And then of course we went through the stage where, don't buy a petrol engine car, buy diesel, because it's about 50p a gallon cheaper or something. Now 90% of all cars on the roads are diesel and now it's more bloody expensive. I mean from 10 years ago we should all be riding about in electric cars.

P5: Do you know that the first generation of nuclear power stations all made a net energy loss. More dumper truck fuel, and men's sarnies, and metal that went into them. And that's without taking into account decommissioning. So less energy came out than ever went in.

P2: That's why we should never listen to scientists!

P5: No, politicians, mate! …

P11: A lot of electric cars I mean-.

P5: Yeah you've still got to make the electricity haven't you?

P11: Yeah, but it's how you make it that counts.

P5: Well that's what I mean. But at the moment we're making electricity by gas and coal.

P11: It's stupid ways really because we've got about 20 different ways of making electricity and none of them are affordable at the moment.

P2: We face a huge energy shortfall…

P5: You know the only people on the planet with a long term plan for that? The Indians, they're working on this thing call a Thorium reactor. To me the single reason it should be pursued is that it will burn the waste that we have at the moment. There's 300,000, no-. Anyway there's a load of material on Earth which will kill you if you go near it for the next million years. And a Thorium reactor will burn it.

P4: But even if you tried their new method of saving energy this week, just shut down half the grid…

P5: Anyway India are the only ones who are trying to develop this Thorium-. They realised it would take 50 generations to develop it, so 50 years ago they started to educate the people who would educate the people who would educate the people who would eventually pull this off. And they reckon they're about 10 years away.

P7: Within the group is there an acknowledgement that climate change does exist, and also this thing that we can't do anything about it?

P4: I was going to ask that same question, yeah.

P7: Because I mean, my own opinion… who thinks they can do anything about it on a personal level and do minor things like public transport or whatever…

P2: I believe it exists, however, I think it's largely natural based. I- well that's my opinion.

P5: Well there's opinion you see and then there's hard science.

P2: Well I haven't seen the hard science, you've haven't brought your hard science in here…

P5: Forgive me because it will sound like an insult but I think that opinion is because you want to drive your car and you want to do these things and you want to deny. I mean they call them climate deniers and I think that's the right word.

P2: No it's not that, it's just been such a small finite period of time that we've been producing anything, so I don't believe they can actually physically say, this small period of time has had such a huge shift compared to other things and can't base it on-.

P5: There's no trust in science you see. When I wanted to understand these questions I went to the University and did a degree in physics because I wanted to be able to understand it, but I can totally appreciate the way you feel. But when someone presents to me, I can look at the evidence and stuff like that and so I can say it's true, and they you have to believe me, it's such a [expletive] situation. Everyone should just be educated with science.

P12: I've seen figures but how many millions of gallons of hydrocarbon fuels are being burnt every hour; that scares me.

P2: There's a difference between using our resources and worrying about resource depletion, which is what I'm more worried about that climate change.

P5: It's the same thing.

P2: No, they're different. Because climate change is I believe natural based. Whereas resource depletion is us digging up and using stuff…

P5: It's the waste products of that very process that are causing the climate change…

Researcher: … What comes to mind when thinking about options for tackling global warming?

P5: I'd just, again, back to Branson's book; I've just changed completely on that. I joined the Green Party thinking I could do something about it, but it's just head and brick wall. Because what individuals can do is very little. You can drive your car less and you can do this and you can maybe try and fly less, but this is nothing compared to-. I then realised that the only thing realistically is vote with our wallets by supporting the companies who do have a big-, can actually do something. You know, Coca Cola, they sell millions of bottles per hour or something like that. They can do something. And we can influence them by voting with our wallet. So to me I can't think of any other way that you can have any serious-.

P12: At least they're bottling up carbon dioxide aren't they?

P5: Yes!

Researcher: What do you think Ron?

P11: I do think that most individuals can make a difference, in lots of small ways. You know we're generating some of our own electricity for our own homes. Millions of millions of people are doing it-.

P2: It starts to make a difference.

P11: If you just have a combination, of probably a small generator, there's various ways of producing it, not necessarily the petrol engine. Small wind generators, solar cells, and that sort of thing. It's very easy and economical to at least cut down 50% of your electricity needs, easy. And very cheaply, for a few hundred quid. You don't have to have a £10,000 wind mill in your garden and you don't have to have £10,000 worth of solar cells on your roof. To distribute your electricity in a proper manner throughout the 24 hour period, not all when you're having your breakfast or watching Coronation St. It's very easy for every single household to reduce their electricity needs to reduce their electricity needs by a minimum of 50% for a few hundred quid. And you work out how many millions of households-. I mean an average household, probably it's costing them £30 a week for electricity, you know, some more than that, some less than that… Just to cut that down to £15. And it must make enormous amount of difference throughout the whole world if everybody did it.

P5: It's also decentralising it.

P2: So there's 2 ways to obviously look at that side of things. One is do the homeowners… thing and I think a lot of it there's beginning to get a lot more aware when things get advertised and people notice. And my mum ended up getting solar panels because the feed-in-tariff was advertised. Ok that turned out to be a lot of people taking advantage of that… But it did get people generating… It does seem to be making money, it's a nice sunny day so… But that's the thing, you've got to rely on the sun. If the sun's not there then it doesn't really work.

P5: The 4th generation PV is coming out, I mean when they first started they were talking about 12% efficiencies. And the stuff they're selling now is up to 22%. There's all sorts of things in prototype now that will raise that even more.

P11: ... Even in totally overcast, hardly no sun whatsoever and you'll get about 95% charge as if there was a full sun on. And like you say some of them are producing about up to 25% efficiency now.

P9: You have to be a young person really I think, to take this on. Because it is an expensive out-lay in the beginning so if you're over 50, really you're not going to get a lot of benefit out of it...

P11: I do think they are overpriced though...

P9: But the thing that struck me last year when I was on holiday and I was going through part of Shropshire where there are new houses and each of-. I had to look twice. Each house at the front had like a small windmill. On the roof. All in a straight line. And what I found out was were small generators which were enough to power that house. And there were about 20...

P2: That was going to be my other point. We're building lots of houses each year. If we get them, I mean-. House builders unfortunately are wanting to build them cheaply, so there's got to be some way to encourage them. Either by people generally-.

P5: But there is, there's a mechanism in place. The planners are allowed to demand-. I think it's called a BRIAM rating or something. They can say to developers, they say well we want to build this, and they say well yes you can build this. And they can just arbitrarily say you have to reach BRIAM excellent. And when you do that when they design it, they get points. For instance, if it's a sculptured bath which uses less water they get a point for that, and then if it's well insulated they get a point for the insulation value and stuff like this. And the net thing is when they've done the design, if they get enough points, they can call it BRIAM excellent or BRIAM reasonable. But the thing is they're not doing it. They'd do it for me if I wanted to build a house... the planners in Norwich would say oh we want BRIAM excellent. But if... come along they'll let them build any [expletive] they like...

P7: We haven't talked about our own individual choice about reducing our own carbon foot-prints, and I don't know what people actually do do. I use my bike as much as I can do-.

P5: Me too.

P7: I try not to use the car. We've got a community small holding group in the village where we produce a lot of stuff locally including livestock, things like that... And you know, I try not to buy rubbish from China, for instance, because it's come from the other side of the world. And it's being produced by people not getting fair wages and things like that... And that's encouraging the growth of what they're doing which I think is dreadful anyway. We can all make changes to our lifestyles, cut out so many visits to the supermarkets and make proper choice about what we do purchase.

Researcher: ... Were there any other options for tackling global warming that we haven't mentioned? ...

P12: I think the thing is getting rid of the carbon dioxide being produced. I mean there's natural processes on the Earth for sinking the carbon dioxide... The sea...

P5: Something we haven't mentioned of course is... decentralisation. Apparently the Green Party are very hot on this transition thing and ideas that the sources of lots of the problem is the way we do business, globally. And they're saying that if you start with... the Norwich pound and you have an economy for Norwich and it discourages buying things from China and things like that.

P12: It's called anarchy if you take it to the extreme isn't it?

P7: Talking to people two generations, or even only generation apart from us, a lot of communities were self sustaining in what they produced and they wouldn't have to get stuff from the other side of the world.

P5: Yeah, I mean the market place in Norwich could be selling food that's grown round Norwich. It should be shouldn't it? It's still like that in France...

P4: Only because it goes back what you said earlier about business, it has to be driven by governments and taxation. For example, Coca Cola only changed the plastic in their bottles because they got an environmental rebate or something for doing it. And it goes back to what you said about builders. When they build the council housing they're doing at the moment, yes solar panels, probably heat pumps, wonderful. Then a similar type builder comes along, cheap bricks, cheap blocks, minimum standards because-. And it's ridiculous it shouldn't even be allowed. The minimum standards should be there and that's the end of it. It just has to come from legislation, and I think the tax benefits, like Volkswagen did it first. But others are doing it now. The more recyclable a car is, the lower the tax is. And they have to accept their own stuff back if it can't be recycled... You're stuck with your own problem unless you make it all recyclable, so they did... Yes the individual makes great changes, I agree, all of you said I would love my own little windmill in my back garden. There all great little things that we can all do, but as said earlier, human nature, a lot of people will never do those things. But the big businesses that chuck out all of the steam, the smoke and the dirt, they can be made to change with environmental changes through taxation...

Appendix 2.2 Criteria Coding

Appendix 2.2.1 Specialist Criteria Coding

Specialist	Criteria or principle	Subgroup	Group
A	Cost	Cost	Economic
	Democratic compatibility[†]	Ownership and control	Ethical
	Demonstration	State of knowledge	Feasibility
	Impact on global warming[†]	Global temperature reduction	Efficacy
	Political acceptability	Political acceptability	Political
	Public acceptability[†]	Social acceptability	Social
	Social impact progressivity[†]	Distributive justice	Ethical
B	Co-benefits[†]	Co-benefits	Other
	Emissions reduction[†]	Greenhouse gas reduction	Efficacy
	Political feasibility	Political viability	Political
	Public investment	Public investment	Economic
	Social inequality reduction	Distributive justice	Ethical
	Unintended environmental risks	Environmental side effects	Environmental
C	Affordability	Cost	Economic
	Feasibility	Technical feasibility	Feasibility
	Foreseeable environmental impacts	Environmental impacts	Environmental
	Political, social and legal feasibility	Political viability	Political
	Scale of effectiveness	Efficacy of intended effects	Efficacy
	Unintended or unanticipated risks	Environmental side effects	Environmental
D	Economic cost	Cost	Economic
	Efficacy of intended impacts	Efficacy of intended effects	Efficacy
	Ethical questions raised	Ethical questions	Ethical
	Unintended consequences	Environmental side effects	Environmental
E	Economic cost[†]	Cost	Economic
	Efficacy and completeness[†]	Global temperature reduction	Efficacy
	Lead-time	Development time	Feasibility
	Public acceptability	Social acceptability	Social
	Climatic response time[†]	Climatic response time	Efficacy
	Safety	Environmental impacts	Environmental
F	Cost[†]	Cost	Economic
	Climate change impacts reduction[†]	Climate change impacts reduction	Efficacy
	Political and technical feasibility	Political viability	Political
	Public acceptability	Social acceptability	Social
G	Centralised or distributed control[†]	Ownership and control	Ethical
	Efficacy uncertainty[†]	Greenhouse gas reduction	Efficacy
	Intergenerational equity‡	Intergenerational equity	Ethical
	Socioeconomic impacts[†]	Socioeconomic impacts	Social
	Transboundary effects[†]	Transboundary impacts	Ethical
	Unintended environmental impacts[†]	Environmental side effects	Environmental
H	Economic feasibility	Commercial viability	Economic
	Environmental impacts	Environmental impacts	Environmental
	Social support	Social acceptability	Social
	Technical feasibility	Technical feasibility	Feasibility
I	Environmental risk	Environmental impacts	Environmental
	Practicality[†]	Technical feasibility	Feasibility

	Sustainability	Economic sustainability	Economic
J	Affordability	Cost	Economic
	CO_2 concentration stabilisation	Greenhouse gas reduction	Efficacy
	Public perception	Social acceptability	Social
	Safety	Environmental impacts	Environmental
K	Cultural acceptability	Cultural acceptability	Social
	Global temperature maintenance	Global temperature reduction	Efficacy
	Governance‡	Governance	Political
	Human impacts‡	Human impacts	Social
	Political acceptability†	Political acceptability	Political
	Resource availability	Resource availability	Resource
	Risk of adverse effects	Environmental impacts	Environmental
	Technical know-how	State of knowledge	Feasibility
L	Cost effectiveness	Cost effectiveness	Economic
	Ensemble (un)certainty	State of knowledge	Feasibility
	Global warming reduction	Greenhouse gas reduction	Efficacy
	Social acceptability	Social acceptability	Social
	Unintended consequences	Environmental side effects	Environmental

All listed criteria are as such except where: † indicates that the corresponding criterion was also used as a principle; and ‡ indicates a principle. In cases where a criterion overlapped with another, the aspect emphasised during the interview was used to categorise the criterion.

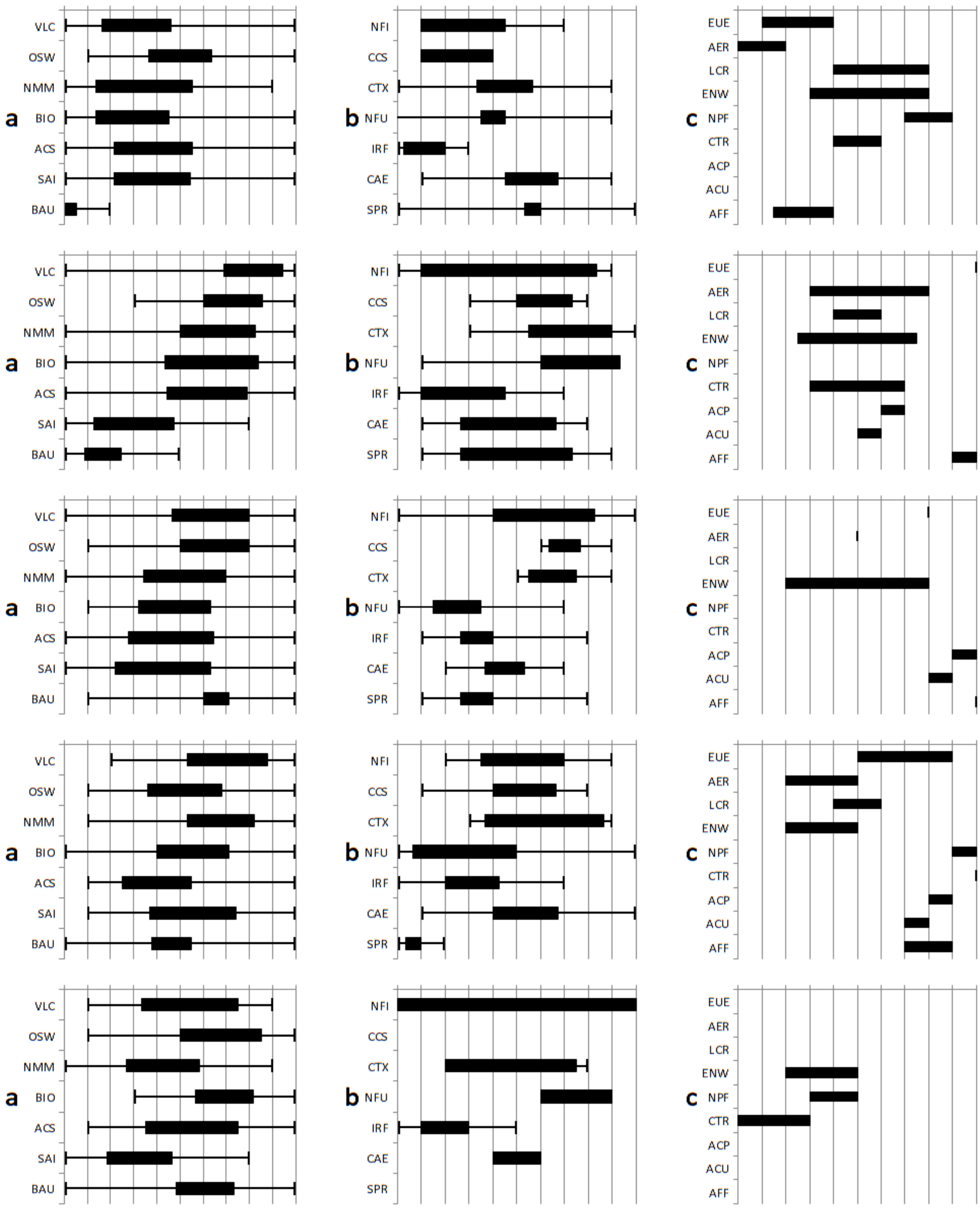
Appendix 2.2.2 Citizen Criteria Coding

Criteria	Subgroup	Group
Affordability	Cost	Economic
Availability	Availability	Ethical
Carbon footprint	Carbon footprint	Environmental
Cost-benefit ratio	Cost-benefit ratio	Economic
Dangerousness	Impacts on humans	Safety
Duration of effect	Duration of effect	Efficacy
Ease of operation	Technical feasibility	Feasibility
Economic efficiency	Cost-effectiveness	Economic
Environmental impacts	Environmental impacts	Environmental
Fairness in practice	Distributive justice	Ethical
Global warming reduction	Global temperature reduction	Efficacy
Impact on lifestyles	Social acceptability	Social
Impact reversibility	Impact reversibility	Environmental
(Inter)governmental cooperation	(Inter)governmental cooperation	Feasibility*
Investment return	Investment return	Economic
Legislation	Political viability	Feasibility*
Monitoring	Ownership and control	Ethical
Moral obligation	Morality	Ethical
Moral pursuit	Morality	Ethical
Openness to abuse	Abuse	Ethical
Political acceptability	Political acceptability	Feasibility*
Political will	Political viability	Feasibility*
Practicality	Technical feasibility	Feasibility
Public acceptability	Social acceptability	Social
Public convincement	Social acceptability	Social
Set-up cost	Cost	Economic
Scalability	Technical feasibility	Feasibility
Side effects on humans	Side effects on humans	Safety
Speed of effect	Climatic response time	Efficacy
Subsidisation	Public investment	Economic
Unforeseen impacts	Environmental side effects	Environmental
Workability	Technical feasibility	Feasibility

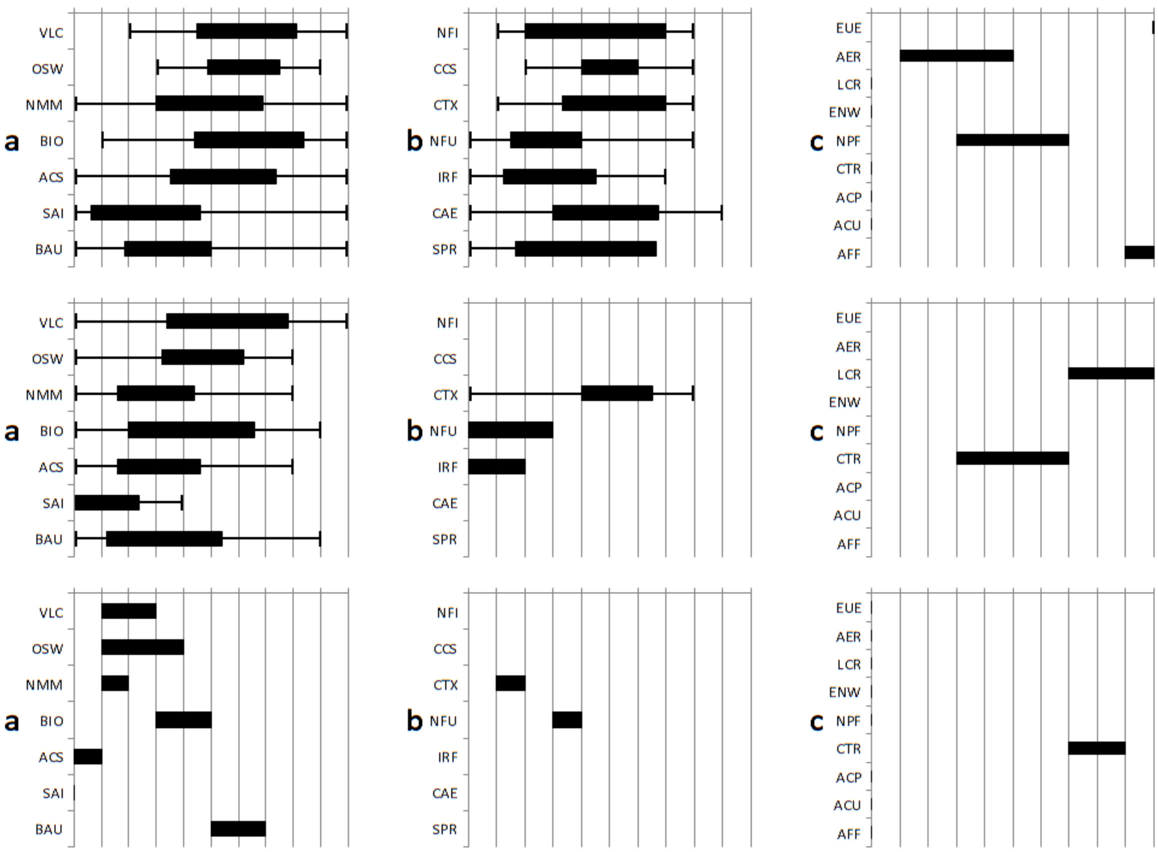
Political criteria (marked *) developed as part of feasibility criteria group by citizens.

Appendix 2.3 Option Performance by Criteria

Appendix 2.3.1 Option Performance by Criteria (Specialists)

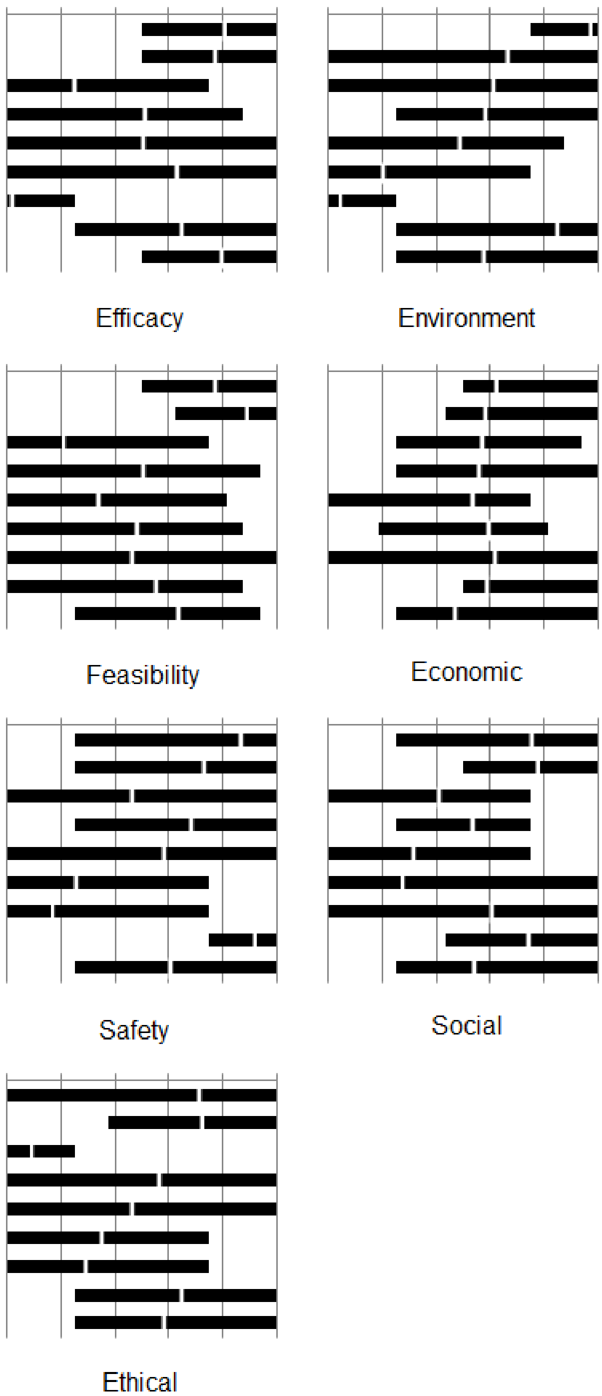


Appendix continues overleaf.



Order of rows: (1) efficacy criteria; (2) environment criteria; (3) feasibility criteria; (4) economic criteria; (5) political criteria; (6) social criteria; (7) ethical criteria; (8) co-benefits criterion. Order of panels: (a) core options; (b) discretionary options; (c) additional options. Acronyms: afforestation (AFF); agricultural emissions reduction (AER); air capture and storage (ACS); air capture set carbon price (ACP); biochar (BIO); business as usual (BAU); carbon tax (CTX); closed-loop air capture (ACU); cloud albedo enhancement (CAE); coal energy with carbon capture and storage (CCS); cultural transformation (CTR); end-use efficiency enhancement (EUE); enhanced weathering (ENW); iron fertilisation (IRF); low carbon research and development (LCR); national policy framework (NPF); new market mechanism (NMM); nuclear fission energy (NFI); nuclear fusion energy (NFU); offshore wind energy (OSW); space reflectors (SPR); stratospheric aerosol injection (SAI); voluntary low carbon living (VLC).

Appendix 2.3.2 Option Performance by Criteria (Citizens)



Order of options: voluntary low carbon living; offshore wind energy; new market mechanism; biochar; air capture and storage; stratospheric aerosol injection; business as usual; afforestation; nuclear fusion energy.

Appendix 3 Published content from this thesis

Appendix 3.1 A review of climate geoengineering appraisals (in WIREs Climate Change; reused here with permission)

Advanced Review

A review of climate geoengineering appraisals

Rob Bellamy,[1*] Jason Chilvers,[1] Naomi E. Vaughan[1] and Timothy M. Lenton[2]

Deliberate large-scale interventions in the Earth's climate system—known collectively as 'geoengineering'—have been proposed in order to moderate anthropogenic climate change. Amidst a backdrop of many ways of framing the supposed normative rationales for or against their use, geoengineering proposals are undergoing serious consideration. To support decision makers in the multitude of governance considerations a growing number of appraisals are being conducted to evaluate their pros and cons. Appraisals of geoengineering are critically reviewed here for the first time using a systematic literature search and screen strategy. Substantial variability between different appraisals' outputs originates from usually hidden framing effects relating to contextual and methodological choices. Geoengineering has largely been appraised in contextual isolation, ignoring the wider portfolio of options for tackling climate change—spanning mitigation and adaptation—and creating an artificial choice between geoengineering proposals. Most existing appraisal methods do not adequately respond to the post-normal scientific context in which geoengineering resides and show a strong emphasis on closed and exclusive 'expert-analytic' techniques. These and other framing effects invariably focus—or close down—upon particular sets of problem definition, values, assumptions, and courses of action. This produces a limited range of decision options which seem preferable given those framing effects that are privileged, and could ultimately contribute to the closing down of governance commitments. Emergent closure around particular geoengineering proposals is identified and argued to be premature given the need for more anticipatory, responsible, and reflexive forms of governing what is an 'upstream' domain of scientific and technological development.

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INTRODUCTION

Deliberate large-scale interventions in the Earth's climate system—known collectively as 'geoengineering'—have been proposed in order to moderate anthropogenic climate change. Scientific, political, private, and public interests in geoengineering proposals are rising against a backdrop of many ways of framing the supposed normative rationales for or against their use. These include desires to avoid 'dangerous' climate change using geoengineering that would otherwise seem unattainable amidst insufficient mitigation efforts or concerns that the lure of geoengineering 'techno-fixes' might induce a 'moral hazard' whereby mitigation efforts are further neglected.[1,2]

The term geoengineering encompasses a wide range of distinct technology proposals which can broadly be classified into 'carbon' and solar' variants, yet its definition remains ambiguous. In the absence of a thorough treatment of the term and its different linguistic framings we begin to map out its complex etymology in the next section of this paper. Whatever framings are constructed and used—be they normative, linguistic, or otherwise—geoengineering proposals are fast becoming a feature of visions on

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how to tackle climate change. Indeed, the new representative concentration pathway (RCP) scenarios to be used in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) already assume at least two of the carbon geoengineering proposals—large-scale afforestation (RCP4.5) and bio-energy with carbon sequestration (BECS) (RCP2.6)—will be used, in addition to 'other technologies that may remove CO_2 from the atmosphere' in extended concentration pathway (ECP) 3PD.[3]

Geoengineering proposals are undergoing serious consideration by prominent institutions and governments around the world.[4-6] To support decision makers in the multitude of necessary governance considerations a growing number of appraisals are being conducted to evaluate the pros and cons of the different proposals and possible future pathways of technological development. A host of approaches are on offer for appraising geoengineering, ranging from established and exclusive 'expert-analytic' methods, such as benefit-cost analysis and risk assessment, to newer and inclusive 'participatory-deliberative' methods, such as citizens' panels and consensus conferences. Much as with the different courses of action they seek to evaluate, however, appraisals themselves are highly sensitive to different framing precommitments and effects.[7]

Through contextual and methodological choices expert-analytic and participatory-deliberative methods of appraisal alike can frame inputs that range from 'narrow' to 'broad' and outputs that range from 'closed' to 'open'.[8] These choices amount to often overlooked 'instrumental framing conditions', which can exert considerable inadvertent or deliberate power on the results of appraisal. Appraisal inputs relate to the diversity of legitimate conditioning knowledges included, such as disciplines, perspectives, purposes, procedures, criteria, and the options or course(s) of action themselves. Appraisal outputs provide assessments of the performance of different courses of action and vary in their degree of 'reflexivity'—i.e. the extent to which diverse frames and pre-commitments shaping knowledge commitments are conveyed, transparently acknowledged, and openly reflected upon.[9] Closed outputs correspondingly produce 'unitary and prescriptive' decision support, closing down on particular course(s) of action; while open outputs produce 'plural and conditional' decision support, instead opening up the diversity of available pathways and their different sensitivities.[10]

While some closure on which course(s) of action to commit to is ultimately necessary, it can marginalize the diversity of conditioning knowledges and result in premature 'lock-in',[11,12] and conflict between divergent values and interests.[10] Such was the case with the appraisal of a previously emergent suite of technologies: genetically modified (GM) organisms and crops. There, narrowly framed and closed expert appraisals of risk with no consideration of alternative options ignored deeper public concerns over 'upstream questions' about the purposes, visions, vested interests, equity, and social implications of scientific and technological development.[13,14] These concerns were recognized only when it became too late to influence developmental trajectories, resulting in an European Union (EU)-wide moratorium on GM crops.

Much like the early stages in the development of GM crops before it, the science and proposals of geoengineering can be considered 'upstream'. That is to say that significant research and development on them has not yet taken place; many of their possible impacts have not yet been explored; and as yet there are few salient media or public discourses. This makes geoengineering proposals very sensitive to appraisal as knowledge of both their technical and social science is immature. Here we undertake a timely and critically reflexive review of geoengineering appraisals for the first time, examining the role of instrumental framing conditions in shaping appraisal inputs and outputs, and ultimately epistemic commitments for particular kinds of response to climate change. We do so with particular attention to four key dimensions by which appraisals are framed: (1) the definition of the problem or issue in question and the purposes of science and technology in addressing it (context); (2) the appraisal methods and criteria used; (3) the particular options or courses of action being appraised; and (4) reflexivity with which results are conveyed. The extent to which these framing conditions narrow or broaden, and close down or open up the results of appraisal will be discussed, together with recommendations for further research and ultimately, the implications for governance.

DEFINING GEOENGINEERING

The idea of control over the Earth's weather and climate predates the modern concept of 'geoengineering' by millennia.[15] It has a rich history in ancient mythologies and religions, including those of Ancient Greece and the Roman Empire. Once powers bestowed by gods, control over weather and climate is now sought through technology. Indeed, this hubristic shift in humanity's relationship with nature was presaged by renowned physicist of Ancient Greece, Archimedes, who is believed to have said: 'Give me a lever long enough and a place to stand, and I will move the world.'

Following the discovery of the greenhouse effect in 1824 by Joseph Fourier and its later experimental demonstration by John Tyndall; in 1908 Svante Arrhenius proposed deliberately enhancing the greenhouse effect by burning more fossil fuels to enhance agricultural productivity.[16] Political as well as academic interests in potential weather and climate control ensued during the early-to-mid twentieth century, eventually reaching its height in the Cold War. Concerted proposals to 'optimize' weather and climate during this period,[17,18] were, however, followed by proposals to weaponize it during the Vietnam War.

The controversy that followed and was sustained by the emergent environmental movement led to the signing of the 1977 United Nations (UN) international treaty, the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD).[19] The convention, however, specifically reserved the entitlement to use weather and climate modification 'for peaceful purposes' (Article 3.1), helping to maintain modest academic and political interest following the discovery of anthropogenic greenhouse gas-induced climate change in 1960 by Charles Keeling.[20] Indeed, climate modification techniques were initially the only responses to climate change under consideration,[21] with no mention of what has now become the dominant—even totalizing—policy discourse: reducing fossil fuel consumption (mitigation).[22]

The term 'geoengineering' was coined in the early 1970s by Italian physicist Cesare Marchetti and later formally published in the inaugural issue of the journal *Climatic Change* in 1977 to describe a method for 'disposal' of atmospheric CO_2 through injection into sinking thermohaline oceanic currents.[23] The term is a compound noun derived from the prefix 'geo' from the Greek *gê* meaning 'Earth'; and the noun 'engineering' meaning the 'application of science to design'.[24] Until recently geoengineering has been absent from common dictionaries because of its origins and confinement within the epistemic discourses of Earth system science and related academic disciplines.

Following its deployment by various actors and emergence in public discourses on climate change, in June 2010 the term was considered to warrant a common definition in the Oxford English Dictionary. However, defining geoengineering is of course somewhat more complex than the Oxford English Dictionary's modest offering (see Table 1). Here we begin to map out the complex etymology of geoengineering, revealing ambiguities as to what: (1) constitutes geoengineering; (2) best delivers a linguistic framing; and (3) segregates its subset-classes.

While most are in agreement that for an action to constitute geoengineering it must be large in scale, ambiguities exist relating to the issue of intentionality. To David Keith, an action constitutes geoengineering when it is large in scale (e.g., continental to global manipulation) and intentional and countervailing in nature.[22] On the other hand, others argue that neither intentionality nor a countervailing nature is a useful criterion for constituting an action as geoengineering. James Fleming points out that those criteria should not be used to constrain actions already defined by their scale, and which could lead to undesirable as well as desired countervailing ends.[15] Indeed, anthropogenic climate change itself has been considered to be inadvertent geoengineering.[25]

Ambiguities as to what best delivers a linguistic framing for geoengineering and its subset-classes often relates to preferences or semantics. The term geoengineering has been—and still is to some extent—competing with a host of alternative terms, including 'climate modification',[28] 'climate engineering',[29] 'Earth systems engineering',[30] 'planetary engineering',[31] and most recently 'climate remediation'.[32] Climate remediation is a particularly interesting case as it represents an attempt to 'rebrand' geoengineering. It was chosen by some to sit more comfortably alongside the more conventionally termed 'mitigation' and 'adaptation' strategies, but it did not go unopposed in its adoption.[33] Similarly, within its subset-classes the term solar radiation management (SRM) has been rebranded 'sunlight reflection methods' due to concerns over its emotively provocative predecessor.[34] Others have simply used 'geoengineering' itself to refer solely and explicitly to solar geoengineering proposals—and in particular stratospheric aerosols—ignoring carbon proposals in the definition altogether.[26]

Ambiguities as to what segregates subset-classes of geoengineering often relate to proposals' technical and political implications. The UK's Royal Society Report has provided perhaps the most widely accepted definition of geoengineering,[1] having been reaffirmed by the UK Government and the IPCC among others.[4,35] This authoritative report divides geoengineering proposals along technical lines into two classes: carbon dioxide removal (CDR) techniques and SRM techniques. The same report recognizes to a lesser extent a further taxonomic division between geoengineering proposals: those pertaining to Earth systems enhancement or traditional 'black-box' engineering.[36] Others have divided proposals along similar lines but included a third class of 'other'

TABLE 1 | Selected Definitions of Geoengineering

Source	Definition of 'Geoengineering'
NAS[25], p. 433	'[Geoengineering proposals] involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry.'
Keith[22], p. 245, 247	'Geoengineering is the intentional large-scale manipulation of the environment. . . For an action to be geoengineering, the environmental change must be the primary goal rather than a side effect and the intent and effect of the manipulation must be large in scale, e.g. continental to global. . . Three core attributes will serve as markers of geoengineering: scale, intent, and the degree to which the action is a countervailing measure.'
Barrett[26], p. 45	'[Geoengineering] is to counteract climate change by reducing the amount of solar radiation that strikes the Earth. . . [not] by changing the atmospheric concentration of greenhouse gases. . .'
AMS[27] p. 1	'Geoengineering—deliberately manipulating physical, chemical, or biological aspects of the Earth system [to reduce the risks of climate change].'
Royal Society[1] p. ix	'. . .the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming. . .'
Oxford English Dictionary[24]	'The deliberate large-scale manipulation of an environmental process that affects the Earth's climate, in an attempt to counteract the effects of global warming.'

proposals;[27] while others still have further divided those subset-classes into sub-subset-classes based on the broad Earth systems they seek to manipulate, including those concerning the top of the atmosphere, atmospheric or surface albedo, land or ocean,[37] and surface albedo modification (SAM).[38] Some divide proposals differently altogether, according to their 'global commons' or 'territorial' governance implications.[39]

Here we have begun to map out the complex etymology of geoengineering and revealed some of its ambiguities. Indeed this is reflected in the varied public understandings of the term, where just 8% of Americans, British, and Canadians are able to 'correctly' define geoengineering.[40] While recognizing the ambiguities of geoengineering, for clarity this review uses the term to refer to deliberate large-scale interventions in the Earth's climate system in order to moderate climate change; and 'carbon geoengineering' and 'solar geoengineering' to refer to classes of proposals which seek to remove and sequester CO_2 from the atmosphere and to increase the reflection of sunlight back into space, respectively.

THE GEOENGINEERING ISSUES

The ambiguities present in defining geoengineering are joined by a deeper diversity of complex technical and social issues, which pose unique challenges for appraisal. Technical issues of concern relate primarily to the potential effectiveness and impacts of different geoengineering proposals, all of which are subject to significant scientific uncertainties. The speed at which geoengineering proposals can reduce the Earth's temperature is one such consideration about their potential effectiveness. For instance, carbon geoengineering proposals act at a much slower rate than solar proposals, posing reservations about their suitability for moderating abrupt climate changes.[37] Whether or not geoengineering proposals address the 'second CO_2 problem'—ocean acidification—is an another significant consideration about their potential effectiveness. In this case, solar geoengineering proposals do not address the issue, whereas carbon proposals do.[1]

The potential side effects of geoengineering proposals are a particular area of consideration. Stratospheric aerosols, often heralded as the most promising solar geoengineering proposal in terms of their effectiveness, are also deemed high risk due to their risk of depleting of stratospheric ozone.[41] Conversely, large-scale afforestation is thought to be one of the least effective carbon geoengineering proposals but also one of those posing the lowest risk.[22] The side effects of geoengineering proposals do not only vary greatly between solar geoengineering proposals and their carbon counterparts, but also between the individual proposals within those subset-classes. While solar geoengineering proposals are broadly considered to pose more undesirable risks than carbon proposals, this is not always true.[1] Surface albedo changes in urban settlements, for example, would pose far fewer risks to ecosystems than iron fertilization of the oceans.

Social issues of concern to appraisal relate primarily to the legality, economics, ethics, and ultimately public perception of different geoengineering proposals, all of which are subject to greatly divergent perspectives and values. The legality of geoengineering, and in particular stratospheric aerosols, is sometimes called into question with reference to treaties such as the Long-Range Transboundary Air Pollution Convention and the 1990 amendment to the Clean Air Act.[42] While there are often calls for geoengineering to be regulated as much as possible under existing mechanisms, these older treaties did not account for geoengineering during their conception and could be renegotiated.[43] Others argue that the ENMOD treaty would make any geoengineering illegal,[44] but overlook the treaty's specific preservation of the right to use such techniques for peaceful purposes.[43]

The economics of geoengineering proposals has been described as 'incredible'.[26] In the face of conventional mitigation strategies, some have concluded that many geoengineering proposals would be relatively cheap to implement.[25,45] While the benefits are said to outweigh the costs of solar geoengineering proposals and carbon proposals alike, the benefits of solar proposals have been argued to be greater.[46] On the other hand, considerable uncertainties are cited in opposition to conclusions such as these.[47] Moreover, the seemingly low costs of geoengineering have fuelled concerns about the possible unilateral deployment of certain proposals.[26]

The ethics of geoengineering is invariably complicated by its diverse range of proposals, meaning that not all proposals raise the same ethical issues.[48] The issue of consent, for example, is likely to be limited by the jurisdictions in which they operate such as the global commons or the sovereign territories of states.[39] However, other ethical issues such as the 'moral hazard' do apply to geoengineering more widely. In this case the lure of geoengineering 'techno-fixes' is feared to threaten the further neglect of mitigation efforts,[1,2] echoing earlier concerns that 'defeatist' adaptation efforts could have the same effect.[49] On the other hand, it has been argued that even considering geoengineering could, in point of fact, galvanize mitigation efforts rather than harm them.[1,50]

The technical and social issues relating to geoengineering appraisal ultimately contribute to the overarching issue of public understandings and concerns. Elicited perceptions of geoengineering vary widely with some researchers finding considerable support for geoengineering,[40,51] while others find an overwhelming preference for conventional mitigation efforts.[52] Carbon geoengineering proposals are seen to be broadly preferred over solar proposals, but a diversity of opinion exists as ever in relation to individual proposals within those subset-classes.[50] Indeed, public discourses on stratospheric aerosols have been found to operate within multiple and often conflicting 'frames', with support for research but hesitation to the idea.[53] Despite the range of technical and socioeconomic issues outlined above, it is evident that discourses of geoengineering have to date crowded out the sort of upstream public concerns that have pervaded other novel technologies. It is upon these considerations over the underlying purposes, values, directionality, and equity of geoengineering science and technology—and the extent to which it reflects human needs and concerns—which public responses to geoengineering and other strategies for tackling climate change will ultimately depend.

FRAMING GEOENGINEERING APPRAISAL

Review method

We conducted a review of geoengineering appraisals to date using a systematic strategy for searching and screening articles of relevance. The Web of Knowledge electronic database was searched with the aim of identifying peer-reviewed and gray literature where geoengineering proposals were formally and explicitly appraised. The search used the following parametric terms: 'GEO*ENGINEERING' or 'CLIMATE ENGINEERING'. A total of 272 returned articles were then screened for their relevance to the aforementioned search aims. Forty-nine relevant articles were then further screened for their scope, where articles appraising ≥ 2 specified geoengineering proposals were included within the review. Nine articles met the inclusion criteria along with a further 12 articles included using the same search and screening criteria in a general internet search using the Google search engine, giving a total of 21 articles. Of these articles an overwhelming majority of 18 were identified as fully expert-analytic in nature. In order to more widely reflect on emergent participatory appraisals of geoengineering the initial screen strategy was relaxed to include those participatory processes where individual proposals or geoengineering as a collective was appraised. A further four articles were added accordingly, bringing the total to 25 appraisals under review (see Table 2).

Context: Appraisal Problem Framing and Purpose

The foremost framing condition shaping the appraisal of geoengineering proposals relates to contextual choice in terms of the object of appraisal—i.e., the problem or issue being addressed. These instrumental framing conditions can be highly subjective and set the context and tone of each appraisal. Here we identify

TABLE 2 | Appraisals of Geoengineering Included in the Review.

Number	Source	Appraisal Design and Methods	Notes on Framing
1	Keith and Dowlatabadi[54]	Expert literature review with select nontechnical issues and subjective risk, relating to eight carbon and solar geoengineering proposals	• Climate change impacts contextual frame • Subjective opinion of risks • Concludes stratospheric aerosols have the lowest COM
2	NAS[25]	Expert literature review with marginal CO_2-equivalent mitigation costs, relating to seven carbon and solar geoengineering proposals	• Climate change impacts contextual frame • Costs are based on considerable uncertainties • Concludes all geoengineering proposals are low cost and feasible except space reflectors, and mechanical cloud albedo and stratospheric aerosols are the most promising
3	Keith[22]	Expert literature review with select uncertainties, nontechnical issues and subjective risk, relating to seven carbon and solar geoengineering proposals	• Climate change impacts contextual frame • Subjective opinion of risks • Concludes stratospheric aerosols have the lowest COM
4	Levi[55]	Expert advice with plotting of costs and risks, relating to six carbon and solar geoengineering proposals plus mitigation	• Multiple contextual frames: climate change impacts, rapid climate change, and insufficient mitigation • Subjective plotting of costs and risks • Concludes space reflectors are highest risk and cost, and mitigation is the least risky
5	Bickel and Lane[46]	BCA relating to four carbon and solar geoengineering proposals	• Multiple contextual frames: 'dangerous' climate change, rapid climate change, and insufficient mitigation • Uses different emission controls scenarios and market and ethical discount rates • Concludes mechanical cloud albedo and stratospheric aerosols have the greatest direct benefit-cost ratios, recommending funding for geoengineering research with solar geoengineering a priority owing to its earlier net benefit potential
6	Boyd[56]	Expert MCA using nine criteria (spanning efficacy, affordability, safety and rapidity), relating to five carbon and solar geoengineering proposals	• Multiple contextual frames: rapid climate change, insufficient mitigation • Technical criteria only with subjective scoring and little attention to uncertainty or sensitivities • Concludes iron fertilization is the most effective; mechanical cloud albedo is the most affordable; air capture and storage is the safest; and mechanical cloud albedo and stratospheric aerosols are the fastest acting
7	Robock[57]	Expert advice relating to two solar geoengineering proposals	• Multiple contextual frames: 'dangerous' climate change and insufficient mitigation • Concludes geoengineering may be a bad idea
8	Crabbe[58]	Expert review of modeling simulations applied to coral reefs, relating to 18 carbon and solar geoengineering proposals	• Multiple contextual frames: climate change impacts and insufficient mitigation • Recommends further research into carbon geoengineering proposals, particularly in relation to air capture and storage, biochar and afforestation
9	Feichter and Leisner[59]	Expert literature review relating to three solar geoengineering proposals	• Multiple contextual frames: climate change impacts and insufficient mitigation • Concludes none of the schemes are a sole solution to climate change

TABLE 2 | Continued

Number	Source	Appraisal Design and Methods	Notes on Framing
10	Irvine and Ridgwell[60]	Expert literature review with select pros and cons and subjective risk, relating to five solar geoengineering proposals	• Multiple contextual frames: 'dangerous' climate change and insufficient mitigation • Subjective opinion of risks • Concludes geoengineering should not be relied upon to stop climate change but recommends further research to be prudent in case of emergency
11	Izrael et al.[61]	Expert literature review with subjective assessment (spanning feasibility and efficacy), relating to 13 carbon and solar geoengineering proposals	• Multiple contextual frames: climate change impacts and insufficient mitigation • Subjective opinion of feasibility • Concludes stratospheric aerosols can be the most effective
12	Lenton and Vaughan[37]	Radiative forcing potential calculations relating to 19 carbon and solar geoengineering proposals	• Multiple contextual frames: 'dangerous' climate change and insufficient mitigation • Assumes strong mitigation scenario baseline • Concludes only stratospheric aerosols, mechanical cloud albedo, and space reflectors can return the climate to its preindustrial state
13	Royal Society[1]	Expert literature review with MCA using four criteria (efficacy, affordability, safety and timeliness), plotted and relating to 20 carbon and solar geoengineering proposals; plus telephone interview survey and focus groups exploring public perceptions, relating to three carbon and solar geoengineering proposals	• Multiple contextual frames: 'dangerous' climate change, insufficient mitigation, and 2°C policy target framed the report; geoengineering definitions framed the telephone survey and focus groups • MCA features technical criteria only with subjective scoring • MCA concludes that stratospheric aerosols, space reflectors, air capture and storage, and enhanced weathering are most effective, afforestation is the most affordable, stratospheric aerosols, desert albedo and Carbon Capture and Storage (CCS) are the most rapid, and air capture and storage, urban albedo and CCS are the safest • Survey and focus groups conclude that perceptions of geoengineering were generally negative
14	Moore et al.[62]	Linear response model simulations compare limiting sea-level rise, relating to five carbon and solar geoengineering proposals	• Multiple contextual frames: climate change impacts and climate emergency • Assumes geoengineering does not affect exchange processes between the atmosphere, biosphere, and oceans • Concludes that bio-energy with carbon sequestration is the least risky and most desirable for limiting sea-level rise
15	NERC[50]	Deliberative public dialogue exploring perceptions (spanning public groups, discussion groups, online survey, and open access events), relating to nine carbon and solar geoengineering proposals	• Multiple contextual frames: insufficient mitigation framed the report; pros and cons and climate emergency framed the dialogue • Climate emergency framing may have influenced stated public acceptability of geoengineering • Concludes that carbon geoengineering proposals are preferred to solar proposals, and afforestation and biochar were specifically preferred

TABLE 2 | Continued

Number	Source	Appraisal Design and Methods	Notes on Framing
16	Spence et al.[51]	Face-to-face interview survey exploring perceptions, relating to geoengineering proposals as a collective[1]	• Multiple contextual frames: 'dangerous' climate change and Climate Change Act framed the report; geoengineering definitions framed the interviews • Uses simple quantitative measures • Concludes that most people do not know what geoengineering is, but would support it
17	Bellamy and Hulme[52]	Online survey and focus groups exploring perceptions, relating to geoengineering proposals as a collective[1]	• Rapid climate change contextual frame used in the article and online survey and focus groups • Presents geoengineering as one option of a range of possible responses to climate change • Concludes geoengineering is unfavorably perceived
18	Fox and Chapman[63]	Expert literature review and ranking applied to engineering feasibilities, relating to 10 carbon and solar geoengineering proposals	• Multiple contextual frames: climate change impacts, rapid climate change, and insufficient mitigation • Arbitrary ranking of feasibilities • Concludes afforestation is the most feasible proposal
19	GAO[5]	Expert technology assessment (spanning maturity, effectiveness, cost factors, and consequences), relating to 14 carbon and solar geoengineering proposals; plus online survey and focus groups exploring public perceptions, relating to four carbon and solar geoengineering proposals	• Multiple contextual frames: climate change impacts, rapid climate change, and insufficient mitigation framed the report; geoengineering definitions framed the online survey and focus groups • Includes foresight exercise using scenarios to elicit views of the future of geoengineering research • Technology assessment concludes that all geoengineering proposals are at TRL 2, except stratospheric aerosols which are the least mature (TRL 1) and air capture and storage which is the most mature (TRL 3) • Survey and focus groups concludes that most are unfamiliar with geoengineering but would be open to research, while demonstrating concern about safety and governance
20	Irvine et al.[38]	AOGCM simulations compare global and regional effects, relating to three solar geoengineering proposals	• Multiple contextual frames: climate change impacts, insufficient mitigation, and 2°C policy target • Limitations to regional modeling of effects • Concludes none of the schemes reverse climate changes under a doubling of CO_2
21	Jones et al.[64]	AOGCM simulations compare climatic impacts, relating to two solar geoengineering proposals	• Multiple contextual frames: climate change impacts and alternative to mitigation • Limitations to cloud modeling • Concludes geoengineering is unlikely to avoid significant regional climate changes
22	Mercer et al.[40]	Online survey exploring perceptions, relating to solar geoengineering proposals as a collective[1]	• Multiple contextual frames: societal responses to climate change, inexpensive, and risks framed the article; pros and cons and climate emergency framed the online survey • Risk of constructed preferences • Concludes the public supports research into solar geoengineering

TABLE 2 | Continued

Number	Source	Appraisal Design and Methods	Notes on Framing
23	Parkhill and Pidgeon[53]	Deliberative workshops exploring perceptions, relating to one solar geoengineering proposals: stratospheric aerosols[1]	• Societal responses to climate change contextual frame used in the workshops • Presents geoengineering as a risk issue • Concludes that participants show a reluctant acceptance of a delivery-mechanism test-bed for stratospheric aerosols
24	Vaughan and Lenton[65]	Expert literature review with select efficacies and feasibilities, relating to 19 carbon and solar geoengineering proposals	• Multiple contextual frames: rapid climate change and insufficient mitigation • Assumes strong mitigation scenario baseline • Concludes that geoengineering is not an alternative to mitigation, but could complement it
25	Russell et al.[66]	Expert literature review with select ecological impacts, relating to five carbon and solar geoengineering proposals	• Climate change impacts contextual frame • Concludes that research on ecological impacts of geoengineering is needed before large-scale field trials or deployment

AOGCM, atmosphere–ocean general circulation model; BCA, benefit-cost analysis; COM, cost of mitigation; MCA, multi-criteria analysis; TRL, technology readiness level.
[1]Appraisals not identified in the initial search and screen strategy.
Contextual frames related to the article context frame or method context frame were stated. We have been necessarily selective in the information provided in this table.

six groups of geoengineering appraisal context or problem 'frames' identified across the appraisals under review (see Table 3). All of the appraisals framed the issue broadly around climate change in scientifically defined terms and the need to alleviate its potential risks, echoing the narrow framings given to other previously emergent sciences and technologies.[14] Within this domain risk-framing articles varied in their choice of illustrative risks. Issue frames ranged from unspecified or specified climate change impacts to special climate 'emergency' conditions, including the onset of rapid or 'dangerous' climate change or climate 'tipping points'. The majority of appraisals were also framed around assumptions of 'insufficient mitigation' efforts, while a minority were also framed around the climate policy targets such as the UK Climate Change Act or the 2°C warming above preindustrial limit. Few appraisals were framed around broader societal responses to climate change or geoengineering as an alternative to mitigation.

Each of these context frames represents particular definitions of the problem, sets of values and assumptions, and visions of the future—while ignoring others—when it comes to the future circumstances under which geoengineering the climate might be considered. Obvious exclusions include the alternative purposes of geoengineering technologies associated with profit, social control, military applications, and so on; anticipation of the (often unintended) social and ethical implications; and recognition of the complex and indeterminate social, cultural-institutional, and

TABLE 3 | Frequency of Different Context Frames in Geoengineering Appraisals

Context Frame	Frequency of Frames
Climate emergency	15
Insufficient mitigation	15
Climate change impacts	13
Climate policy	3
Societal responses to climate change	2
Alternative to mitigation	1

Frames are elicited from article introductions and methods. Most appraisals used multiple frames, which are counted here separately.

geopolitical futures embedded within such visions. These 'imaginaries' are particularly potent in participatory processes, where different context frames can exert significant power upon participants' appraisals through the phrasing of questions. For instance, during the NERC Experiment Earth? public dialogue facilitators and experts described the future using a climate 'emergency' frame, which is likely to have influenced the perceived acceptability of geoengineering proposals through the implicit implication of necessity.[67] Similarly, it is a climate 'emergency' frame that underpins apparent public support for solar geoengineering reported in the online survey by Mercer et al.[40] Concordantly, with the majority of geoengineering appraisals adopting the 'insufficient mitigation' frame, necessity of at least researching geoengineering is implicitly implied.

TABLE 4 | Frequency of Different Geoengineering Appraisal Methods

Appraisal Method	Frequency of Appraisals
Expert-analytic	18
Participatory	5
Expert-participatory	2

Appraisal Methods and Criteria

Beyond the construction of broad contextual problem frames lie specific methodological choices and selection of criteria to judge different courses of action in tackling climate change. These powerful instrumental framing conditions set the lens through which each appraisal is conducted. Of the original 21 geoengineering appraisals identified for review an overwhelming majority (18) were identified as expert-analytic in nature (see Table 4). That is to say they were conducted by experts without the inclusion of publics, and utilized methods of appraisal that can be construed as relatively constrained, opaque, and often quantified in their treatment of the issue. These methods ranged from computer modeling to economic assessments to expert reviews and opinions to multi-criteria analysis (MCA). A further two of the geoengineering appraisals reviewed were expert-analytic in principal focus, but were supported by minor participatory elements. These expert-participatory methods included an expert review of the geoengineering literature and a simple MCA conducted by the UK Royal Society and a technology assessment conducted by the US Government Accountability Office. Each featured surveys and focus groups to elicit perceptions of geoengineering.[1,5] The one dedicated participatory-deliberative appraisal identified in the initial search was the NERC Experiment Earth? public dialogue.[50] A further four participatory articles were added following a relaxation of the screening strategy.

The expert-analytic appraisals of geoengineering can be classified among those involving calculations or computer modeling, expert reviews and opinions, economic assessments, and MCA. Those appraisals using calculations or computer models are naturally constrained to the disciplinary study of technical criteria involving the efficacies of geoengineering proposals. Methodological choices made within these appraisals inevitably involve making contestable assumptions about the futures in which geoengineering would operate. The use of the Bern carbon model in producing CO_2 scenarios, for instance, assumes that geoengineering would have no impact on the carbon exchange processes between atmosphere, biosphere, and oceans.[62] Similarly, the use of strong mitigation or balanced use of energy sources as scenario baselines assumes certain social and technical developments while ignoring other possible futures and sensitivities.[37,64]

Sources of uncertainty in climate models relating to the representation of baseline conditions, forcings, and sensitivities are well documented,[68] but pose some specific issues for modeling the efficacies and impacts of geoengineering. Atmosphere–ocean general circulation models (AOGCMs) are widely used and considered to provide credible projections of future temperature change at large spatial scales. However, projections made at smaller spatial scales such as regional precipitation patterns are poor, confounding conclusions made in relation to regional geoengineering impacts such as those by surface albedo changes.[38] Moreover, considerable uncertainties remain such as the modeling of cloud formation and opacity, confounding conclusions made in relation to specific geoengineering proposals such as cloud albedo enhancement.[64]

Expert reviews and opinions dominate the expert-analytic category of geoengineering appraisals, seeking to synthesize disparate existing information,[65] apply it to a novel context,[58] or use it to inform expert opinion.[61] While each of these objectives is capable of closing down the range and quality of outputs through the inherently selective choice of information for inclusion or exclusion, expert opinions hide a range of subjectivities. A frequent opinion aired in appraisals of geoengineering relates to the risk of side effects. For instance the purported risks of a particular solar geoengineering proposal—space reflectors—vary wildly, from very low,[54] to low,[22] to moderate,[1] and to high.[55,60] The subjective reasoning that underpins these discreet and seemingly 'matter of fact' statements is often under-explained and unaccounted for. Similarly, the reasoning and methods behind arbitrary rankings for different geoengineering proposal feasibilities lack transparency.[63]

The US Government Accountability Office (GAO) technology assessment review undertook a notably different approach in exploring the envisaged future of research on geoengineering.[5] While still constrained to expert opinions only, the assessment recognized the roles that subjectivities and imaginaries play in technology advancements and developed a foresight exercise in which four scenarios were constructed and engaged with. Despite the limited range of scenarios and participants this exercise represents an important step forward in opening up visions of the range of possible futures in which geoengineering could reside.

A limited number of economic assessments have been made to appraise geoengineering, seeking to identify the benefits and/or costs of different proposals. Here those methods involve calculating the marginal CO_2-equivalent cost of mitigation (COM)[25] or benefit-cost analysis (BCA).[46] Critiques of appraisals based solely on economic efficiency criteria are well established, often citing their ignorance of wider issues as well as an inadequate or even inappropriate representation of 'nonmarket goods'.[69] Moreover, economic assessments of novel proposals such as those within geoengineering can more generally suffer from 'appraisal optimism' because of systematic biases in underestimating costs.[70]

Economic assessments are particularly open to instrumental framing conditions relating to their treatment of sensitivities and the discounting of time. While the BCA conducted by Bickel and Lane does include a number of different emission controls scenarios as well as market and ethical discount rates, these assumptions rely upon huge uncertainties in the literature.[46] Furthermore in a demonstration of these methodological framings influencing outputs, another BCA using the same dynamic integrated model of climate and the economy (DICE) but different assumptions led to conflicting conclusions. Where stratospheric aerosol injection achieved an admirable benefit-cost ratio of 25 to 1 in the study by Bickel and Lane, Goes et al. concluded that the solar geoengineering proposal failed benefit-cost analysis under no less plausible assumptions.[47,71]

Multi-criteria analyses can account for a much wider range of appraisal criteria than BCA or other expert-analytic methods, but are no less susceptible to instrumental framing conditions. Here, the chosen diversity of criteria and weightings given to them is critical, constraining the appraisal scope and privileging certain criteria above others. Both the Royal Society and Philip Boyd have performed MCA appraisals relating to the same, loosely defined technical criteria such as efficacy, affordability, safety, and timeliness.[1,56] While these appraisals fail to take advantage of the wider range of possible criteria for inclusion within MCA, including a plethora of possible social, political, and ethical considerations, a much broader critique befalls the use of MCA itself. Quantitative methods of appraisal, such as MCA, require criteria of the same dimensionality in order to use a mathematical approach. That is to say, if the multiple units of appraisal are not compatible, the unit-less outcome amounts to adding apples and oranges.[72]

The participatory-deliberative appraisals of geoengineering can be classified among those involving surveys, focus groups, and deliberative workshops, each seeking to elicit public and/or stakeholder views and perceptions of geoengineering. Appraisals employing surveys were the most frequent of those attempting to open up inputs, doing so via online instruments, telephone interviews, or face-to-face interviews. While not strictly deliberative these often quantitative methods are also constrained by a limited appreciation of the participant reasoning that underpins claims. For instance, the seemingly discreet finding that 72% of people somewhat or strongly support solar geoengineering proposals, together with limited information on possible variables, tells us little about supportive or confounding influences on that claim.[40] Moreover, survey research cannot ensure the derivation of opinion on emergent issues such as geoengineering, instead often deriving 'constructed preferences' via information provision.[73]

Focus groups can offer much deeper explanations of what underpins public understandings and concerns about geoengineering, but are still focused in terms of a stated agenda for discussion. For instance, Bellamy and Hulme introduce geoengineering as an option for counteracting climate tipping points, seeking to elicit policy preferences.[52] The Royal Society sought to elicit the perceived benefits, risks, and uncertainties about geoengineering.[1] The GAO focus groups sought to elicit reactions to geoengineering proposals, support or opposition, and how to best make decisions about geoengineering in government, industry, and as individuals.[5] While broadening the range of appraisal criteria they are still bound by their choice of focus for the discussion. Concurrently the recruitment of participants also constitutes an important framing effect. For instance, the use of university participants in convenience sampling, an accessible and popular strategy in psychological research, can produce unrepresentative western, educated, industrialized, rich, and democratic ('WEIRD') representations of humanity.[52,74]

The deliberative workshops on geoengineering offer the least constrained methods of eliciting public perceptions of and concerns about geoengineering. While still employing focus to direct the deliberations, these methods allow participants to frame the discussions to some extent and thereby facilitate deeper exploration of perspectives. Such methods are just as susceptible to other framing effects as other methods, however, including through the provision of information. As with all participatory methods, the provision of information with respect to emergent issues about which little is known is a critical framing effect, risking the formation of constructed preferences rather than derived opinions.[59] For instance, the provision of selected pros and cons of different geoengineering proposals is technically focused, marginalizing other issues such as ethics.[50,67]

Parkhill and Pidgeon refer to this as 'treading a fine line' between providing sufficient information for discussion without influencing participants' views.[53]

Appraisal Options

The scope of options—or courses of action—included within appraisals of geoengineering is a critical instrumental framing condition narrowing or broadening the possible future pathways for addressing climate change. Geoengineering options were selected for inclusion or exclusion from the appraisals under review on the basis of a number of normative rationales. For instance, they have been selected on the basis of their being 'promising suggestions',[59] their 'promise for affecting global climate',[46] their prominence in 'popular and scientific media',[56] and their 'plausibility',[53] or on no apparent basis at all.[5] Appraisals of geoengineering assessed a mean average of 8.5 different options per article, composed of an even four solar and carbon options per article. However, from an analysis of the frequency of different individual geoengineering proposals featured in appraisals we identify an emergent focus—or closing down—on particular proposals (see Figure 1).

The frequency of different geoengineering proposals featured in appraisals shows an emergent tiered distribution, with certain proposals clearly receiving more attention than others. Three of arguably the most controversial geoengineering proposals occupy positions in the top four most frequently appraised proposals: stratospheric aerosols, space reflectors, and iron fertilization. Stratospheric aerosols are by far the most frequently appraised proposal, appearing in 22 of the appraisals and on average five times more frequently than other proposals.

The appraisals appear to close down upon certain geoengineering proposals and not others, while many fail to open up the decision context to include legitimate alternative options. Alternative courses of action are commonly and narrowly represented by other geoengineering proposals, ignoring the necessary and wider portfolio of climate change strategy options—mitigation and adaptation—and facilitating contextual isolation. This creates an artificial 'yes/no' choice between geoengineering proposals. The few exceptions to this open up the decision context by appraising geoengineering alongside single (e.g., carbon capture and storage)[1] or multiple courses of mitigation action.[52]

Reflexivity

The extent to which appraisals of geoengineering acknowledge the myriad of instrumental framing conditions bearing upon their outputs is a decisive framing condition in itself. The 'reflexivity'—or degree of transparent acknowledgement—with which those conditioning knowledges are conveyed directly impacts on the legitimacy of any conclusions or

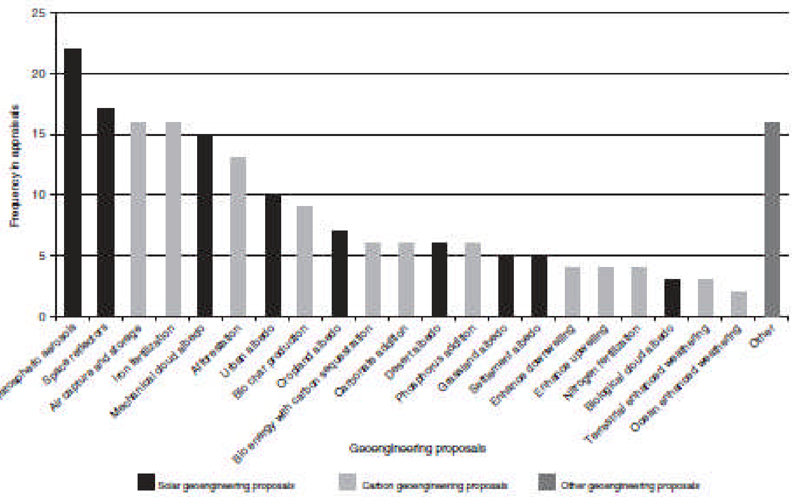

FIGURE 1 | Frequency of different geoengineering proposals featured in the appraisals reviewed. Note: 'other' geoengineering proposals are those featured only once. Supplementary appraisals (i.e., the participatory appraisals undertaken by the Royal Society[1] and GAO[5] in addition to their primary expert-analytic appraisals) are counted here as separate appraisals.

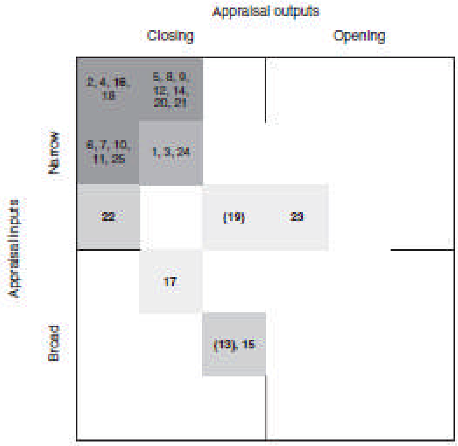

FIGURE 2 | Breadth of inputs and openness of outputs in geoengineering appraisals (after Stirling et al.[8]). Bold numbers represent participatory appraisals; bold, bracketed numbers represent expert-participatory appraisals; and plain numbers represent expert-analytic appraisals. Note: numbers are in ascending chronological order and relate to appraisals in Table 2. Appraisal positions in the grid are necessarily interpretative, and not definitive but indicative. Appraisal breadth was assessed as either low or high in a 2 × 2 matrix in relation to the scope with which appraisals accounted for the character of the decision context and the diversity of legitimate knowledges; then positioned relative to one another within a 3 × 3 sub-matrix. Appraisal openness was assessed as either low or high in a 2 × 2 matrix in relation to the reflexivity with which instrumental framing conditions are conveyed and outputs made, then positioned relative to one another within a 3 × 3 sub-matrix.

recommendations drawn from them. Levels of reflexivity—in terms of opening up the inputs and outputs of appraisals—were identified as low for the majority of those geoengineering appraisals under review (see Figure 2). Substantial variability between different appraisals' outputs, but relating to the same geoengineering issues, was found and can be attributed to the hidden uncertainties and subjectivities bound within the instrumental framing conditions. For instance, where iron fertilization is viewed as relatively effective by Philip Boyd, it is viewed as relatively ineffective by the Royal Society.[1,56] Moreover, where the Royal Society reports the mean performance scores with small error bars given by a number of experts, the full range and diversity of scores as well as their reasoning underpinning those means are hidden and unaccounted for.[1]

Ultimately, these low levels of reflexivity amount to many appraisals making unitary and prescriptive decision recommendations, closing down on particular course(s) of action. Each of the geoengineering appraisals under review recommends further research. However, some go further and produce definitive recommendations as to which geoengineering proposals are best in different respects or deserve particular attention or funding. Of those appraisals, recommendations were advanced on the basis of the technical factors of efficacy, feasibility, economics, safety, or the social factor of preference. Stratospheric aerosols, space reflectors, mechanical cloud albedo,[37] or iron fertilization are heralded as the most effective.[56] Bio-energy with carbon sequestration is heralded as the least risky and most desirable for limiting sea-level rise.[62] Stratospheric aerosols, afforestation,[63] air capture,[5] or all geoengineering options except space reflectors are heralded as the most feasible.[25] Mechanical cloud albedo and stratospheric aerosols are heralded as the most cost effective.[46,56] Air capture and storage is heralded as the safest.[56] Afforestation and biochar production are heralded as preferred by the public.[50] Each of these recommended decision options seems preferable given the respective instrumental framing conditions upon which they are built.

DISCUSSION AND RECOMMENDATIONS

Contextual Isolation

Different contextual frames were identified in the appraisals under review, hinting at the diversity of supposed normative rationales for considering the use of geoengineering. Such framings can have a profound impact on appraisal inputs and outputs, as demonstrated by the likely influence of the climate 'emergency' frame on participants used during the NERC Experiment Earth? public dialogue.[67] A narrow emphasis on this climate 'emergency' frame as well as the 'insufficient mitigation' frame was found among the appraisals under review. These frames suggest implicitly that conventional measures for mediating climate change are not enough, and that geoengineering is required. This may therefore artificially enhance the perceived acceptability of geoengineering proposals. Correspondingly, issues of reflexivity arise with respect to these framings: why use these context frames and not others? What are the normative rationales underpinning the use of those frames and what might their framing effects be? Recognizing the many different ways in which geoengineering can be contextually framed and the effects these can have will strengthen the transparency and legitimacy of appraisal conduct and output.

While the appraisals emphasize certain context frames above others, isolating them from the diversity of the supposed normative rationales for or against the use of geoengineering, so too do they isolate geoengineering from the wider decision context in which it resides: moderating climate change. By narrowly appraising geoengineering proposals only against one another, legitimate alternatives are ignored and contextual isolation is facilitated. To avoid this false 'yes/no' choice between geoengineering proposals the necessary and wider portfolio of climate change strategy options—spanning mitigation, geoengineering, and adaptation options—should be addressed. Opening up and appraising the full range of courses of action available to decision makers broadens the inputs to appraisal and better acknowledges the complexity of the issue.

Handling Uncertainty

The propriety of different methods in appraisal can be ascertained by examining the decision context characterizing a given issue. The upstream nature of geoengineering proposals, together with the large Earth system uncertainties and high stakes of climate change itself—and of its intentional manipulation on top of that—places geoengineering firmly within the realms of 'post-normal' science.[75,76] It is important in decision contexts such as these to include within appraisals axiological factors (value judgments) from an 'extended peer community' or all those with a stake in the issue and not simply experts. While there is no doubt that participatory forms of appraisal are equally susceptible as technical-analytic ones to instrumental framing conditions and the closing down of wider policy discourses,[10,77] participation by definition brings other voices, perspectives, knowledge, and visions of the future into the process which challenges existing assumptions and interests, whether that be related to normative or substantive reasons.[78]

However, the overwhelming majority of the appraisals under review were identified as expert-analytic in nature. This is not to say that such expert-analytic methods are not welcome or needed; on the contrary, such methods are an essential and necessary contribution to the appraisal of technical issues. Rather this observation recognizes the need for a balancing of appraisal methods, to include more participatory-deliberative appraisals of geoengineering. Only by including such methods can we begin to fully account for the great system uncertainties and high stakes that characterize the post-normal state in which the upstream science of geoengineering resides.[75,76]

Appraisals of geoengineering more widely reflect methodological responses to the incertitude of decision making. Stirling et al. outline four characteristics of incertitude relating to knowledge about probabilities and outcomes.[8] Unproblematic knowledge of both probabilities and outcomes characterizes a 'risk' issue and expert-analytic methods such as risk assessment and BCA are considered appropriate methods of decision support. With respect to geoengineering, however, knowledge about either probabilities or outcomes or both is often problematic and highly uncertain. This characterizes geoengineering as an 'uncertainty' issue, an 'ambiguity' issue, or an 'ignorance' issue respectively, each where expert-analytic methods are deeply insufficient when used in isolation.[79] Accordingly, a host of different methods of appraisal for decision support are considered more appropriate. Under uncertainty decision heuristics or sensitivity analyses might be considered. Under ambiguity foresight scenario workshops or multi-criteria mapping might be considered. Under ignorance broader aims such as institutional learning and adaptive management might be considered.[8]

Lock-In and Diversity

As the aforementioned analysis has shown, low levels of reflexivity as identified in the appraisals of geoengineering under review contribute to the production of unitary and prescriptive decision recommendations. This closure around particular sets of hidden values or assumptions—be it around climate models, scenario baselines, selective information consideration, subjectivities of risk, valuations, criteria for inclusion or exclusion, presentation of findings, information provision, choice of focus, recruitment of participants, choice and characterisation of options, or a host of other framing effects not necessarily covered in this review—produces variably limited ranges of decision options which seem preferable given those framing effects that are privileged.[10] Accounting for and acknowledging these framing effects through reflexive declaration will enhance transparency and ultimately the rigor of accountability in relation to any decisions made from recommendations therein.[8]

The scope of options addressed in appraisals of geoengineering already demonstrates closure around specific proposals, and in particular stratospheric aerosol injection. Whatever the supposed rationales for consistently including stratospheric aerosols in appraisals more often than any other geoengineering proposal—be it because of its normative reasons of plausibility or promise, seemingly substantive reasons of efficacy or economics, or any other reason—we have demonstrated that these assertions are at this stage simply too uncertain and sensitive to instrumental framing conditions to justify closure around a quintessentially upstream idea. Furthermore, this premature closure could contribute to stratospheric aerosols becoming a salient or even synonymous icon of geoengineering, whereby support or opposition to geoengineering in general is judged by one proposal. Indeed, some already use the term geoengineering synonymously with stratospheric aerosols.[26]

The outputs of many geoengineering appraisals can be considered examples of different types of 'decision justification', whereby appraisals can exert inadvertent, tacit, or deliberate influences of power on decision making through their various framings and prescriptive policy advice.[10,80,81] This could contribute to a premature closing down of governance commitments on geoengineering, or even more widely on responses to climate change. In contrast, to open up choices to decision makers is to widen the scope of appraisal inputs and outputs and ultimately inform governance with enhanced rigor, transparency, and accountability. Plural and conditional policy advice instead accounts for alternative decision options and the different frames under which each might appear favorable or unfavorable.

Geoengineering proposals currently exist as a diverse range of ideas open to different actors in science, policy, and society as a plurality of possible imagined futures. As an upstream suite of technology proposals, however, they are particularly sensitive to these instrumental framing conditions and could easily be quickly and prematurely closed down, locking us in to certain technological trajectories but not others.[11,12] Ultimately, potentially unsung divergent values and interests in such a lock-in could cause controversy.[10] Appraisals should therefore broaden the inputs into and open up the outputs from appraisals of geoengineering, placing them in the lower right hand quadrant of Figure 2. A number of appraisal methodologies already exist which actively seek to address instrumental framing conditions in such a way, including expert-analytic methods such as multi-criteria mapping,[82] participatory-deliberative methods such as scenario workshops,[83] Q-method,[84] and Stakeholder decision analysis,[85] and the analytic-deliberative hybrid deliberative mapping.[86]

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Ultimately, the issues addressed in appraisals of geoengineering pose unique challenges for the governance of geoengineering research and development. Indeed, the diversity of issues is considered to rule out any single mode of governing geoengineering.[39] As an 'upstream' suite of technology proposals geoengineering more broadly exemplifies the 'technology control dilemma', in that predictive governance arrangements made prior to any actual developments will unavoidably fail to account for unanticipated evolutions.[1,87] Indeed, this dilemma has beset previously emergent technologies such as nuclear energy and GM crops. In these cases, narrowly framed expert considerations of performance and risk ignored deeper public concerns about the values, visions, and vested interests driving scientific and technological development.[13] Recent study comparing public dialogues on geoengineering and many other areas of emerging science and technology shows these concerns over the purposes of science, trust, inclusion, speed and direction of innovation, and equity to be highly durable and in need of reflection.[88]

Accounting for these public concerns and the values, visions, and vested interests that drive science, however, can contribute to an enhanced societal capacity for foresight, and ultimately anticipatory rather than predictive governance.[89] The test case for this anticipatory governance has been the emerging science and technologies of nanotechnology,[90] the 'control of matter at dimensions of roughly 1–100 nm, where unique phenomena enable novel applications'.[91] In recognizing the coproduction of socio-technical knowledges,[92] as well as the normative, substantive, and instrumental arguments in favor of public participation in appraisal, experiments with the anticipatory governance of nanotechnology using forward-looking and inclusive participatory methods of expert and public engagement alike have yielded promising results.[93]

The sentiments of anticipatory governance were captured to some extent in proposed governing principles for geoengineering: the Oxford Principles.[94] The principles call for (1) geoengineering to be regulated as a public good, (2) public participation in geoengineering decision making, (3) disclosure of geoengineering research and open publication of results, (4) independent assessment of impacts, and (5) governance before deployment. Welcomed with caveats by the UK Government's House of Commons Science and Technology Committee, ambiguities with respect to the nature of the public participation and the flexibility of governance regimes have since been further developed by the Asilomar Conference Recommendations on Principles for Research into Climate Engineering Techniques 2010.[4,95]

CONCLUSION

In this review, we have critically examined appraisals of geoengineering with a view to understanding framing effects and promoting greater reflexivity in appraisal conduct. Appraisals of geoengineering can be seen to be closing down around particular sets of values and assumptions with respect to the instrumental framing effects of contexts, methods and criteria, and options. Each of these framing effects can exercise differing and considerable powers on the outputs of appraisal, artificially promoting seemingly preferable decision option given those framing effects that are privileged. We recommend a greater awareness and acknowledgement of the power these framing effects can bear upon appraisals of geoengineering. Such reflexive accountability and responsibility will invariably enhance the transparency and rigor of appraisal outputs and ultimately contribute to more robust decision making.

Ultimately this review raises issues for the governance of geoengineering. The post-normal scientific context that characterizes decision making on geoengineering demands the inclusion of axiological factors and therefore public participation. This is in addition to the other powerful normative, substantive, and instrumental reasons for public participation.[78] The narrowly framed considerations of performance and risk offered by traditional technocratic expert-analytic methods of appraisal (and some participatory ones as well) and the predictive governance that they support cannot therefore account for unanticipated evolutions in geoengineering.[1,87] This technology control dilemma can be mitigated through ongoing and reflexive anticipatory governance in accounting for the values, visions, and vested interests driving the issues, before it is too late to influence developmental trajectories.

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Appendix 3.2 'Opening up' geoengineering appraisal (in Global Environmental Change; reused here with permission)

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'Opening up' geoengineering appraisal: Multi-Criteria Mapping of options for tackling climate change

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ABSTRACT

Concerted efforts have begun to appraise deliberate, large-scale interventions in the Earth's climate system known as 'geoengineering' in order to provide critical decision support to policy makers around the world. To date geoengineering appraisals have employed narrowly framed inputs (such as context, options, methods and criteria) and 'closed' output reflexivity often amounting to unitary and prescriptive policy recommendations. For the first time, in this paper we begin to address these limitations by 'opening up' appraisal inputs and outputs to a wider diversity of framings, knowledges and future pathways. We use a Multi-Criteria Mapping methodology to appraise carbon and solar geoengineering proposals alongside a range of other options for responding to climate change with a select but diverse group of experts and stakeholders. Overall option rankings are found to vary considerably between participant perspectives and criteria. Despite these differences, the ranks of geoengineering proposals are most often lower than options for mitigating climate change (including voluntary behaviour change and low carbon technologies). The performance of all options is beset by uncertainty, albeit to differing degrees, and it can often be seen that better performing options are outperformed under their pessimistic scores by poorer performing options under their optimistic scores. Several findings contrast with those of other published appraisals. In particular, where stratospheric aerosol injection has previously outperformed other geoengineering options, when assessed against a broader diversity of criteria (spanning all the identified criteria groups) and other options for responding to climate change it performs relatively poorly. We end by briefly exploring the implications of our analysis for geoengineering technologies, their governance, and appraisal.

1. Introduction

Resurgent interest in the prospect for 'geoengineering' the climate follows a long history of desire to bring the forces of nature under human control (Fleming, 2010). Once believed to be powers that only the Gods of ancient mythologies and religions could bestow, the ideas of climate control are now thought to be within the reaches of science and technology. Research into climate modification reached its height during the Cold War, where plans to 'optimise' climate (e.g. Rusin and Flit, 1960) were succeeded by experiments to weaponize weather during the Vietnam War (Fleming, 2006). Today such research is concerned with tackling anthropogenic climate change through geoengineering, an idea that gained prominence in 2006 when Nobel laureate Paul Crutzen, frustrated by insufficient mitigation efforts, proposed artificially enhancing the Earth's albedo through stratospheric aerosol injection (Crutzen, 2006). Geoengineering comprises a disparate collection of deliberate, large-scale interventions in the Earth's climate system that can broadly be divided amongst 'carbon geoengineering' proposals which seek to remove and sequester atmospheric CO_2, and 'solar geoengineering' proposals which seek to increase the reflection of sunlight away from the Earth (Royal Society, 2009). Together with the risk of climate 'emergencies' and other normative rationales for geoengineering, concerted efforts have begun to appraise the pros and cons of these different proposals in order to provide critical decision support to policy makers around the world.

A recent review of existing geoengineering appraisals reveals that they hold a number of significant limitations relating to their

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narrowly framed inputs and 'closed' output reflexivity (Bellamy et al., 2012). Appraisals of geoengineering have been conditioned by narrow problem framings, in which particular issues, such as the predominant 'insufficient mitigation' (e.g. Crutzen, 2006) and 'climate emergency' (e.g. Blackstock et al., 2009) frames, exclude alternative problem definitions. Concurrently, appraisals have almost exclusively focused on assessing single geoengineering options (e.g. Keith et al., 2005; Lampitt et al., 2008; Robock et al., 2009) or on developing internal comparisons between geoengineering options (e.g. Keith, 2000; Lenton and Vaughan, 2009; NERC, 2010). Existing appraisals have thus consistently isolated geoengineering proposals from their decision context by omitting the wider portfolio of options for responding to climate change, spanning mitigation and adaptation.

Methods for appraising geoengineering have most often closed down around 'expert-analytic' procedures such as computer modelling (e.g. Moore et al., 2010), cost–benefit analysis (e.g. Bickel and Lane, 2009), expert review (e.g. Robock, 2008) and multi-criteria analysis (e.g. Boyd, 2008), and employed technical criteria such as those spanning efficacy, feasibility and economics (Bellamy et al., 2012). While such methods make a vital contribution to the appraisal of technical issues and in building an essential knowledge-base for geoengineering governance, they do not adequately respond to the 'post-normal' scientific context in which geoengineering resides (Funtowicz and Ravetz, 1993). The high uncertainties and high stakes of climate change, heightened further by its intentional manipulation through geoengineering, limit the propriety of 'normal' basic or applied science. These uncertainties and stakes demand that appraisals include axiological factors, not only from experts but from all those with a stake in the issue, from an 'extended peer community'.

Inputs to appraisals of geoengineering, such as perspectives, procedures, options and criteria, have been found to be narrow in focus (Bellamy et al., 2012). These often unacknowledged instrumental framings can exert significant power upon appraisal outputs, 'closing down' around those particular knowledges and marginalising the true diversity of perspectives that bear upon the issue (Stirling, 2008). Following on from this, there has been a tendency for the outputs, such as findings, conclusions and recommendations, from many of the aforementioned appraisals of geoengineering to have been closed down as well. This can lead to unitary and prescriptive decision support, and overlook the diversity and sensitivities of decision pathways that are available, possible or imaginable (Stirling et al., 2007).

Ultimately these contextual, methodological and un-reflexive instrumental framings have amounted to the closing down upon particular values and assumptions, whilst excluding the diversity of others. In many cases, it has led to conclusions that close down upon particular options, principally stratospheric aerosol injection: a controversial solar geoengineering proposal to inject reflective sulphate particles into the stratosphere and cool the Earth (e.g. Keith, 2000; Lenton and Vaughan, 2009; Izrael et al., 2009). Closure in 'upstream' technologies such as geoengineering can risk premature 'lock-in' and conflict between divergent values and interests, as was previously the case with the proposed commercialisation of genetically modified (GM) crops (Wilsdon and Willis, 2004).

Methods of appraisal exist which actively seek to address issues of closure such as those pervading appraisals of geoengineering, by 'opening up' to the wider diversity of framing conditions and perspectives that permeate the issue. These include, but are not limited to, scenario workshops (Ogilvie, 2002), Q-method (McKeown and Thomas, 1988), Stakeholder Decision Analysis (Burgess, 2000) and Deliberative Mapping (Burgess et al., 2007). This article presents the findings of research using another such innovative methodology, Multi-Criteria Mapping (MCM) (Stirling, 1997; Stirling and Mayer, 2001), a multi-criteria option appraisal method designed to map the diversity of contrasting perspectives bearing upon complex policy issues.

This research on geoengineering builds on the successful development and application of MCM in the anticipatory appraisal of analogous complex and uncertain emerging technologies, including agricultural biotechnologies (Stirling and Mayer, 2001), medical health technologies (Davies et al., 2003), and energy-related technologies (Stirling, 1994; Chilvers and Burgess, 2008). Whilst acknowledging other possible framings, such as climate optimisation or weaponization the research sought to appraise carbon and solar geoengineering proposals using the broader framing of 'responding to climate change' and the diverse portfolio of alternative options it opens up. This was done with a range of specialist and stakeholder perspectives, as part of a wider research project also involving public participation.

2. Methods

As with other multi-criteria methods, the MCM method comprises four stages: (1) developing a set of options to appraise; (2) characterising a range of criteria against which to assess those options; (3) scoring the relative performance of the options against those criteria; and (4) assigning a weighting to each criterion to indicate their relative importance. The procedural methods of the MCM method are explained more fully in Stirling and Mayer (2001), but aspects specific to this study demand detailed discussion here.

2.1. Framing

In recognising the narrow contextual limitations of earlier appraisals of geoengineering, the study adopted an open problem framing and broad issue context. Rather than defining the 'problem' as a leading one of 'insufficient mitigation' or the risk of a 'climate emergency', for example, it was framed as an exercise in 'responding to [global] climate change' which allowed for a diversity of perspectives to bear upon it. This problem framing extended to the adopted issue context, where geoengineering proposals were presented alongside alternative options for responding to climate change; as well as allowing for the introduction of additional options defined by the participants themselves.

Options for responding to climate change can be broadly divided amongst mitigation, adaptation and geoengineering strategies. The Intergovernmental Panel on Climate Change (IPCC) defines *mitigation* as 'implementing policies to reduce greenhouse gas emissions and enhance sinks' (IPCC, 2007, p. 84). The inclusion of sink enhancement in this definition reflects some ambiguity relating to the categorisation of carbon geoengineering proposals, some of which share this aim. In this study we disaggregate them and restrict mitigation to mean options available to reduce greenhouse gas emissions, spanning energy conservation/efficiency and low carbon energy production.

The IPCC defines *adaptation* as '...measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects' (IPCC, 2007, p. 76). The objectives of adaptation, however, are fundamentally different to those of geoengineering and mitigation. Whilst those latter strategies seek to avoid or lessen climate change itself, adaptation seeks to address its impacts. Adaptation options are responses to temporally and spatially specific impacts, experienced as weather events, and therefore cannot be presented alongside geoengineering and mitigation options at a meaningful resolution. For example, stratospheric aerosol injection and offshore wind energy both seek to tackle or avoid climate change, but constructing flood defences does not. Whilst adaptation strategies could not be meaningfully included in the study as discrete options to appraise, the concept of

Table 1
The definitions of 'core' options (C1–C7) appraised by all participants and 'discretionary' options (D1–D7) appraised by some participants at their discretion.

Option	Definition
C1 Voluntary low carbon living	Promoting voluntary reductions in domestic and commercial energy use.
C2 Offshore wind energy	Increasing the proportion of energy provided by offshore wind turbines.
C3 New market mechanism	Developing a new and expanded market-based carbon trading mechanism.
C4 Biochar	Focusing research and development into the production of biochar and its application to soils.
C5 Air capture and storage	Focusing research and development into the use of technology for capturing CO_2 from the ambient air.
C6 Stratospheric aerosol injection	Focusing research and development into the injection of reflective sulphate particles into the stratosphere.
C7 Business as usual	Continuing with business as usual, with no further adoption of options for responding to climate change.
D1 Nuclear fission energy	Increasing the proportion of energy provided by nuclear fission power stations.
D2 Coal energy with CCS	Focusing research and development into the use of technology for capturing CO_2 at source from coal power stations.
D3 Carbon tax	Increasing and widening taxation of CO_2 emitted during the fuel cycle.
D4 Nuclear fusion energy	Focusing research and development into the use of nuclear fusion for energy generation.
D5 Iron fertilisation	Focusing research and development into the application of iron to the ocean to stimulate algal growth.
D6 Cloud albedo enhancement	Focusing research and development into the use of technology to enhance cloud reflectivity.
D7 Space reflectors	Focusing research and development into the use of reflective mirrors in Earth orbit.

Acronyms: carbon capture and storage (CCS).

adaptation and of adaptive capacities would be implicitly addressed through the inclusion of a baseline 'business as usual' option and its resultant climatic impacts.

A review of options for responding to climate change yielded an extensive range of potential options for inclusion within the study. For practical reasons these options could not be presented for appraisal in their entirety, and so the options were screened against a range of criteria in order to produce a list of discrete options to appraise that were indicative of the diversity of options available. These criteria assessed the diversity of: (1) strategies (geoengineering or mitigation, technological or non-technological, engineered or natural); (2) likely governance (territorial or commons-based operation, centralised or distributed control); (3) policy instruments (regulatory, market-based or voluntary); and (4) novelty/maturity (novel/immature or established/mature). The review yielded seven 'core' options to be appraised by all participants in the study and seven 'discretionary' options to be appraised by participants at their discretion (see Table 1). Options were necessarily presented at different scales of impact and none were presented as 'silver bullets' capable of tackling climate change in isolation.

2.2. The participants

A diverse group of twenty-four specialists and stakeholders were identified by the research team to participate in a series of scoping interviews. Interviewees were identified for their seniority and appreciation of the international context of climate change, and their diversity of perspectives in relation to their: (1) working sector (academia, civil society, industry or government); (2) disciplinary specialism's (natural or social science perspectives relating to general or specific geoengineering proposals or mitigation options); and (3) personal attitudes to geoengineering research (arguments pro or contra geoengineering research as mapped by Betz and Cacean (2012)). Interviewees were screened against these criteria in more depth during a short telephone interview, culminating in the recruitment of twelve diverse specialists and stakeholders who would go on to participate in the full MCM study (see Table 2).

2.3. The interviews

Prior to interview participants were given a booklet detailing the aims and methods of the study, together with definitions of the 'core' and 'discretionary' options to be appraised. Participants were then interviewed on a one-to-one basis at their place of work using the computer software program 'Multi-Criteria Mapper'. The principal researcher guided each participant through the four stage multi-criteria process detailed above, in interviews that lasted between 1 and 3 h. A second set of interviews took place several weeks later in order to present participants with the initial results of the study and to further explore their views in relation to geoengineering appraisal and governance as well as to reflect on their participation in the study.

2.4. Analytical methods

The MCM study produced a variety of quantitative and qualitative data outputs. The quantitative data consisted of 'optimistic' and

Table 2
The participants.

Code	Position	Expertise	Perspective[1]
A	Environmental social scientist	M	A9(−); A73(−)
B	Interdisciplinary climate scientist	M, A, G	A32(+); A52(−); A58(−); A75(−)[†]
C	Earth system scientist	G	A32(+); A87(+)
D	Science and technology social scientist	G	A32(+)
E	Volcanologist	G	A32(+); A87(+)
F	International conservation charity manager	M, G	A32(+)
G	International technology action group manager	G	A9(−); A73(−)
H	International commercial competition manager	G	A32(+)
I	National engineering institution manager	M, G	A32(+)
J	National government civil servant	G	A32(+); A87(+)
K	Local government public sector officer	M, A	A32(+)
L	National government scientific advisor	M, A, G	A32(+); A87(+)

Acronyms: mitigation (M); adaptation (A); geoengineering (G).

[1] Perspective on geoengineering research elicited during scoping interviews. Perspectives coded against argument map by Betz and Cacean (2012). Arguments denoted as pro (+) or contra (−) geoengineering research: mitigation obstruction (A9); insufficient mitigation (A32); irreducible uncertainty (A52); socio-political uncertainty (A58); technical fix (A73); hubris (A75); preparing informed decision (A87).

[†] Participant B was pro researching select carbon geoengineering proposals complementary to mitigation, but contra large scale solar geoengineering.

'pessimistic' scores of option performance given by each participant (taken together as a quantification of uncertainty), and criteria weightings. These data allowed for the production of aggregate scores of option performance rank, calculated using a simple linear additive weighting aggregation model: $R_i = \sum_c S_{ic} \cdot W_c$ where overall performance rank for a given option (R_i) is the sum of performance scores for that option under a given criterion (S_{ic}), multiplied by the corresponding criterion weighting (W_c) (see Stirling and Mayer, 1999). A 'real-time' sensitivity analysis was performed during the interview to assess the effects of different criteria weightings on overall option rankings. Each participant concluded with satisfaction that their chosen weightings accurately represented their perspectives. A second sensitivity analysis was conducted to assess the effects of ranking aggregate optimistic and pessimistic scores on overall rank order, which were found to change very little.

The MCM interviews also produced in-depth qualitative data of the key reasonings, meanings and considerations of all participants in relation to: the overall framing of the problem and options for responding to climate change; the criteria and principles against which the performance of options was judged; the judgements made in scoring the options against criteria; weighting considerations; and reflections on the appraisal process and implications for geoengineering governance. All interviews were audio recorded, fully transcribed and subject to coding analysis using the qualitative data analysis software program Nvivo. As part of this process criteria and principles were coded first into emergent sub-groups of related issues, and second into emergent overall groups of related subgroups. The reasonings underpinning judgements of option performance against each criterion were then explored in the analysis.

3. Results and discussion

3.1. Options and criteria

In addition to the seven core options, ten participants opted to appraise discretionary options, with two participants appraising all seven of them. Seven participants introduced a total of nine 'additional' self-defined options for appraisal. Four of these were carbon geoengineering proposals, two of which were variants of air capture and storage. Another four were approaches to mitigation, and one was a broader 'cultural transformation', to which responding to climate change was considered a co-benefit.

The participants developed a rich diversity of criteria to appraise options for responding to climate change. A total of 61 criteria were developed, which have been coded into 26 emergent subgroups that form part of 8 main criteria groups (see Table 3). The criteria developed in interviews addressed issues spanning, and often transcending, the natural, applied and social sciences, ranging from issues of efficacy and environment, to issues of feasibility and economics, to issues of politics, society and ethics. Whilst the criteria may appear discrete, the participants recognised that each of their criteria represented a complex aggregation of issues and often bore close relations to other criteria.

A total of 23 'principles' were also developed and subsequently classified into 18 emergent subgroups which map onto the same 8 groups of the criteria (see Table 3). 15 of the subgroups were developed initially as criteria but later repeated as separate principles to rule out options deemed unacceptable. The remaining 3 were developed purely as principles, regarding issues of governance, human impacts and intergenerational equity.

Table 3
Classification of criteria and principles into groups and subgroups.

Groups	Subgroups
Economic	Commercial viability; cost[†]; cost effectiveness; economic sustainability; public investment
Efficacy	Climate change impacts reduction[†]; climatic response time[†]; efficacy of intended effects; global temperature reduction[†]; greenhouse gas reduction[†]
Environmental	Environmental impacts[†]; environmental side effects[†]; transboundary impacts[†]
Ethical	Distributive justice[†]; ethical questions; intergenerational equity[‡]; ownership and control[†]
Feasibility	Development time; state of knowledge; technical feasibility[†]; resource availability
Political	Political acceptability[†]; political viability; governance[‡]
Social	Cultural acceptability; human impacts[‡]; social acceptability[†]; socioeconomic impacts[†]
Other	Co-benefits[†]

Notes: All listed are criteria except where † indicates corresponding criterion also used as a principle; ‡ indicates a principle. In cases where a criterion overlapped with another, the aspect emphasised during the interview was used to categorise the criterion.

3.2. Scoring of option performance

3.2.1. Efficacy

Of the core geoengineering options, the efficacy of stratospheric aerosol injection was the most variable. This was in part a reflection of what participants' deemed to be the 'objective' at stake, be it temperature reduction, greenhouse gas reduction or otherwise, culminating in a variety of different efficacy criteria. Participants concerned with a reduction in global temperature (A, E, K, L) or a rapid climatic response time (E) scored the option very highly, with one participant describing it as 'alarmingly easy' (E). The high scores were accompanied by caveats relating to potential difficulties in achieving globally uniform temperature changes. Unsurprisingly, participants concerned with a reduction in greenhouse gases (B, G, J) scored the option very poorly, citing the option's failure to address CO_2 emissions or concentration and the associated problem of ocean acidification. The option was ruled out against efficacy principles by participants A and G. This variability is in stark contrast with other appraisals' consistent claims of high efficacy (e.g. Izrael et al., 2009; Lenton and Vaughan, 2009; Royal Society, 2009).

The efficacy of air capture and storage was also highly variable, but it scored moderately overall. Whilst participants expressed confidence in people's willingness to invest in the technology, much of the uncertainty stemmed from its perceived technological immaturity. Participants cited its feasibility in principle, but raised doubts as to its potential performance at scale owing to resource limitations for processing vast quantities of air and the availability of geological reservoirs for its storage aspect. The option's slow rate of effect and failure to address other greenhouse gases were also cited. These findings too contrast with the high performance rating given by the Royal Society (2009). Biochar performed poorly against efficacy criteria, with many participants citing significant resource and spatial limits to its potential scalability.

Of the core mitigation options, the efficacy of a new market mechanism was the most variable. Whilst generally seen to perform very highly under the assumption that it were successfully implemented through a global international agreement, the perceived likelihood of such an agreement being achieved coupled with an undervalued carbon price and high emissions quotas led to the option also scoring poorly. Participant G viewed the option's potential to reduce greenhouse gas concentrations so poorly as to rule it out on principle.

Offshore wind energy performed moderately, with relatively little variability. Although it was emphasised by participants that none of the options under scrutiny should be viewed as a panacea, it was often stated with particular attention to offshore wind energy. Its heterogeneous geographical potential, inherent intermittency of electricity supply and need for effective integration with a 'smart grid' were cited as key limitations to its reliability. The voluntary low carbon living option performed very poorly, with some variability. Its acute susceptibility to the 'collective action problem', the desire of people to maintain carbon intensive lifestyles, and different priorities of both individuals and nations were also cited. The potential efficacy of the option was seen to be highly unlikely, without 'regulation' (L) or a 'disaster' to prompt changes in behaviour (D).

Business as usual performed consistently very badly, with E, F, G and J ruling the option out on principle for its slow rate of effect, if any, and its failure to reduce greenhouse gas concentrations, global temperature and the impacts of climate change.

3.2.2. Environment

Of the core geoengineering options, biochar scored the most highly against environmental criteria. Whilst some variability was expressed with respect to the possibility of adverse environmental impacts if the option were used at scale, impacts were generally seen to be restricted to soil and air quality, localised and few in number. Air capture and storage also scored relatively highly against environmental criteria, albeit with a greater degree of variability. The risk of 'leaks' and destabilised geological reservoirs featured prominently in interviews, alongside environmental concerns relating to the acquisition of resources demanded over the option's lifecycle. On the other hand, participants noted its likely regulation, monitoring and 'switch off' controllability.

Described as an 'emergency measure' (E), stratospheric aerosol injection performed consistently very poorly against environmental criteria. A swathe of foreseeable and transboundary impacts were raised, including stratospheric ozone depletion; effects on global circulation and regional weather patterns; shifts in the Inter-Tropical Convergence Zone (ITCZ) threatening rainfall in sub-Saharan Africa and the Indian Monsoon; as well as unforeseeable side effects. These risks were often cited from the results of climate model outputs, which were themselves seen to be highly uncertain and conservative. Novel threats such as a 'termination problem', also outlined in Russell et al. (2012), whereby a sudden temperature rise in line with the previously masked atmospheric CO_2 concentration would follow a cessation of stratospheric aerosol injection, as well as the continued impacts of ocean acidification, were also cited. Concern over the 'irreversibility' (H) of many of these environmental risks and the potential 'tipping' (I) of Earth systems into alternate states was also raised. Participant G judged the environmental side effects of the option to be unacceptable, and ruled it out on principle.

The voluntary low carbon living option scored very highly against environmental criteria, with participants often expressing difficulty in thinking of any adverse effects. The inadvertent use of higher carbon goods through the pursuit of low carbon goods was cited as a limitation, as was the possible environmental impacts of using alternatives to carbon. Offshore wind energy also performed highly, with some variability. Risks to birds and marine life were raised alongside more serious concerns regarding the large quantities of infrastructure to be manufactured, deployed, maintained and decommissioned at scale.

A new market mechanism performed reasonably highly against environmental criteria, but with a high degree of variability. Whilst some viewed the option as relatively benign, many others raised the problem of 'perverse incentives' in which certain activities are encouraged, in this case reducing CO_2 emissions, but inadvertently increasing environmental degradation elsewhere through the impacts of incentivised alternatives.

Business as usual performed very poorly, with some variability. Participants acknowledged that the environmental impacts of business as usual, and of the resulting climate changes, would be severe, with participants G, J and K ruling the option out on principle. Participant B was more optimistic about adaptability than others. A particularly interesting discourse that emerged surrounding business as usual was whether it would perform better or worse against environmental criteria than stratospheric aerosol injection. Three distinct positions emerged, with one participant remarking that 'business as usual is never going to be a better option than geoengineering' (E); another that '…the risk is probably about the same' (I); and another that '…with stratospheric aerosols we're actually exacerbating the risks' (B). As well as reflecting uncertainty around the side effects of stratospheric aerosols, this also reflects a complexity of ethical positions relating to geoengineering as a 'lesser evil' as critiqued by Gardiner (2010).

3.2.3. Feasibility

Of the three core geoengineering options, biochar scored most highly against feasibility criteria, albeit modestly and with some variability. Whilst its local scale feasibility was cited, participants expressed potential spatial and practical difficulties in scaling up the operation. Without large scale field trials, it was said, these uncertainties would remain, reflecting sentiments made in Lehmann (2007). Air capture and storage scored highly in principle, with participants C and H noting that they had either held or indeed bought a flask of CO_2 that had been captured from the air. However, the option scored poorly in terms of its technological maturity and the fact that it had not been proven to work at scale. This finding contrasts with the recent US Government Accountability Office (GAO) report, which placed air capture and storage at Technology Readiness Level 3 (GAO, 2011). Limits to that scalability were also cited, with reference to the availability of geological reservoirs. Participant I proposed that this issue could be overcome through 'carbon recycling' rather than storage, through air capture with 'closed-loop utilisation'. However, this proposal would negate the option's negative emissions capabilities.

Stratospheric aerosol injection generally scored poorly against feasibility criteria, but with a considerable range of variability. As with air capture and storage, stratospheric aerosol injection was seen to be highly feasible in principle, but scored very poorly in its potential practice. This finding contrasts with the high engineering feasibility conferred in Fox and Chapman (2011). Whilst one participant commented that '… from a technical point of view I could do it tomorrow afternoon' (I); others cited potential difficulties in achieving the desired particle size and dispersion in the stratosphere, and that these difficulties would not be understood until field trialling had begun. Another participant (E) drew on recent experiences with the Stratospheric Particle Injection for Climate Engineering (SPICE) project, noting that aspects of feasibility that needed to be tested 'outside the lab' would be constrained not only by technical limitations but also social issues.

The voluntary low carbon living option scored relatively highly against feasibility criteria, with some variability. Participants viewed the option as very easy to do both technically and practically on an individual basis, but alongside the caveat that considerable social and economic barriers would constrain its feasibility at scale. Participant I denounced the option as being synonymous with business as usual, and ruled it out on principle. Offshore wind energy also scored relatively highly with some variability. The successes of existing and planned offshore wind energy projects were cited, but so too were maintenance and logistical difficulties in operating them at scale over their lifecycles.

A new market mechanism scored moderately, but with high variability relating to perceived slow development time, complexity at scale and perceived problems with securing an effective carbon price. Participant I noted that this latter issue could be addressed if the option were combined with a variant of air capture and storage which could be used to set the carbon price, as also outlined in Fox (2012), based on the financial cost incurred to 'correct' the economic externality.

Business as usual scored highly against feasibility criteria, much to participants' regret. Some variability was expressed, however, relating to resource limits associated with the unsustainable exploitation practices of business as usual; as well as a likely diminished feasibility under mounting social and political pressure.

3.2.4. Economics

Of the three core geoengineering options, the economics of stratospheric aerosol injection was the most variable. The option's performance depended upon what was included in its base cost, which if considered purely in terms of the resources required to operate stratospheric aerosol injection, it scored very highly. One participant commented:

> '...it's terrifyingly good value for money... just purely on a technological delivery basis it's probably on the order of around a billion dollars' (E).

However, if the base cost included potential economic costs incurred by adverse side effects, it scored poorly. Participants cited the potential need for compensating regions that suffered adverse impacts, as well as the on-going costs associated with a reliance on stratospheric aerosol injection in order to avoid the termination problem. These findings would suggest that the economics of stratospheric aerosol injection are not 'incredible' after all, confirming conjecture by Robock (2008) and conflicting with other consistently favourable claims (e.g. Barrett, 2008; Bickel and Lane, 2009; Keith and Dowlatabadi, 1992; Keith, 2000; Levi, 2008).

Biochar performed moderately against economic criteria, but with a degree of variability. Its economics were seen to depend greatly on the scale at which it would be applied, with larger scale operations seen as increasingly expensive. Participant H noted viable economic markets open to biochar, but cited difficulties in securing sales and investment being experienced by existing companies. Air capture and storage performed poorly against economic criteria, with some variability associated with potential technological breakthroughs, different technology designs and wildly contrasting estimates of cost/tonne of CO_2 captured communicated by air capture proponents and their critics. The overall poor performance contrasts sharply with the possible 'appraisal optimism' (Flyvbjerg et al., 2003) of proponents (e.g. Keith et al., 2005). On the other hand, the option was seen to lend itself to private commercial pursuits, but given the quantities of air that needed to be processed, together with a legacy of infrastructure, maintenance and storage costs, it was viewed as unlikely to ever be cheap.

Of the three core mitigation options, the voluntary low carbon living option scored most highly. Most participants viewed the option favourably as it would not be adopted unless it was affordable. Higher level costs, however, such as running a social marketing campaign were viewed as potentially greater, given their need to compete with the greater marketing budgets of business as usual. A new market mechanism also scored highly, but with some variability. It was noted that its very premise was to be economically efficient, but that existing market mechanisms had suffered from a 'chronically undervalued' (E) carbon price. On the other hand, it was seen to be beneficial for stimulating innovation, and by extension the economy, through new markets and businesses.

Offshore wind energy scored moderately against economic criteria, with some variability surrounding the policy framework in which it would operate. Considerable costs associated with the legislative planning, installation, grid connection, maintenance and decommissioning of offshore wind turbines were cited as reasons for concern alongside high electricity costs passed on to consumers. Despite these reservations, participants noted that achieving economies of scale, future investment and technological advancements would likely reduce these costs.

Business as usual performed poorly against economic criteria, with participants noting its beneficial generation of economic activity, but extensive unintended costs. Participant F deemed the costs that would be incurred to the world by climate change though pursuing business as usual 'would be off the scale', and ruled the option out on principle.

3.2.5. Politics

Of the three core geoengineering options, biochar performed the most highly against political criteria. Participants cited its politically attractive 'win-win sales talk' (C) and the fact that it is already practiced, albeit on a small scale. However, some variability was expressed when considering the option's performance at larger scales of deployment, where more people would be affected by its use. Air capture and storage also performed highly against political criteria. Whilst participants cited no need for multilateral agreements for its use and its compatibility with commercial uptake, politically sensitive risk issues were noted surrounding the siting and safety of carbon storage facilities.

Stratospheric aerosol injection scored very poorly against political criteria. It was seen as an incredibly difficult political issue, even under a best-case scenario where multilateral negotiations would be pursued. Participants expressed significant doubts about its viability, given the diverse cultural and vested interests that have confounded existing attempts to secure a global agreement to mitigate. The fact that no legal framework or governance structures are in place gave rise to concerns over the risk of unilateral deployment, reflecting those aired by the Solar Radiation Management Governance Initiative (SRMGI, 2011). One participant commented that 'In terms of international law, it's a black hole' (C). The global risks that might arise from such an endeavour raised issues of geopolitical tensions and of the need for compensation mechanisms to recompense regions that suffered adverse impacts. Participant K considered stratospheric aerosols to be politically unacceptable, and ruled the option out on principle without sufficient governance to control it.

Offshore wind energy scored the most highly of the three core mitigation options. It was cited as being politically more acceptable than its onshore counterpart, notwithstanding aesthetic objections from coastal communities. The voluntary low carbon living option performed moderately against political criteria, with participants citing its voluntary nature as unlikely to generate political tensions. Concurrently, the option was criticised for lacking political leadership and drive, as well as potential regulation.

A new market mechanism scored moderately against political criteria, but with a high degree of variability. Whilst the option was viewed favourably in that it would not affect citizens in any visible way, difficulties surrounding the willingness of different nations to participate were seen as unlikely to lessen. Participant F also raised the contested issue of historical emissions and the burden of responsibility.

Business as usual scored highly against political criteria. Much as with its performance against feasibility criteria, it was with participants' regret that change was politically undesirable.

3.2.6. Society

Biochar scored reasonably highly against social criteria, with some variability. Its well established use, potential improvements to agricultural yields and publically perceived 'naturalness' were all viewed as positive aspects of biochar. These findings lend support to the positive public perceptions recorded in the NERC

(2010) Experiment Earth? dialogue. However, participants often cited the potential for land-use conflicts with biochar practiced on larger scales, and a number of vocal oppositional non-governmental organisations. Air capture and storage scored moderately, with some variability associated with its safety and its aesthetic value. Public fears of sudden CO_2 release were expressed, citing the 1986 Lake Nyos outgassing as an analogy (BBC, 1986). Participants often used onshore wind turbines as an analogy for the aesthetics of air capture and storage, noting the risk of potential 'NIMBYism' (Gipe, 1995).

Stratospheric aerosol injection scored very poorly against social criteria, with variability relating to its very premise, distribution of effects and deployment. In its best case participants said the option mirrored a natural system, that of a volcanic eruption. Participant E remarked that 'Stratospheric aerosol injection rightly scares the [expletive] out of everybody'. Participant L commented that the very idea was likely to be met with public hostility, whilst participant E cited a 'reluctant acceptance'. This latter view finds resonance in recent public engagement research (Macnaghten and Szerszynski, 2013) and more specifically, with the SPICE project (Parkhill and Pidgeon, 2011). The social inequities risked by an uneven distribution of the option's effects were raised often by participants, citing secondary impacts of environmental risks. Strong opposition from non-governmental organisations was also cited, but participant K added that technological robustness and satisfactory governance could help mitigate concerns. Participants A and G judged the social acceptability and socioeconomic impacts of the option to be unacceptable, and ruled the option out on principle.

The voluntary low carbon living option performed highly against social criteria, as it was seen to be unforced and therefore acceptable. However, participants often noted the option's inherent conflict with people's lifestyles and their deep rooted practices, which would discourage its adoption. Participant K noted that many nations are already living low carbon lifestyles, so such a proposal would be unproblematic. Offshore wind energy scored highly against social criteria, but with some variability. As with the political criteria, it was cited as being more socially acceptable than its onshore counterpart. On the other hand, its cost of electricity to the consumer was cited as being expensive in the face of cheaper, but higher carbon, alternatives.

A new market mechanism scored moderately against social criteria, with some variability. As with the political criteria, it was viewed favourably in that it would not affect citizens in any visible way, but this differed greatly between nations. Participant G also raised concerns about the mechanism's potential for creating unfairly distributed socioeconomic impacts, citing existing Clean Development Mechanism (CDM) projects to develop biofuels. The extent of these risks was judged by that participant to be unacceptable, and they ruled the option out on principle.

Business as usual scored moderately against social criteria, but with some variability. The poverty alleviation brought about through business as usual was seen as socially beneficial, and public perceptions of the resultant climate change itself were viewed as conservative and therefore of limited social concern. However, participants argued that strong opposition from non-governmental organisations would impact, as would the increasingly apparent impacts of climate change. Indeed, the socioeconomic impacts over time were viewed by participant G to be unacceptable, who ruled the option out.

3.2.7. Ethics

Of the three core geoengineering options biochar performed most highly in relation to ethical criteria, scoring moderately with some variability. Its localised nature was seen by participants to be less troubling, even beneficial, compared to those options with global implications. However, biochar was said to potentially pose similar social and environmental risks to biofuels if used at scale, with the imposition of risks and benefits on certain people, and the large-scale reorientation of agricultural production. Air capture and storage performed poorly, with some variability. Ethical concerns were largely related to the option's storage aspect, citing safety aspects of the CO_2 storage. Whilst a 'waste product' was involved, participant D remarked, the option would be beset by similar problems as those experience by nuclear fission energy, with its radioactive waste. This lends support to the additional option of air capture and closed-loop utilisation separately proposed by participant I.

Stratospheric aerosol injection scored very poorly against ethical criteria, with very little variability. It was widely held to pose difficult and unpredictable ethical disputes. The issue of consent was deemed to be a core ethical consideration, reflecting concerns noted by Corner and Pidgeon (2010), with participant D remarking 'I don't envisage a set of circumstances in which you could ever get something that looked like consent, either informed and given, or assumed, in anything like a satisfying way'. The same participant also stated that the ethics of possible unilateral deployment '. . .are tantamount to war'. Participants A and G considered concerns over the option's ownership, control and distributed impacts to be unacceptable, and they ruled the option out altogether.

Of the three core mitigation options, the voluntary low carbon living option scored most highly, with some variability relating to its ability to reduce social inequalities. Participant A noted that the option could be socially progressive depending upon the specific approaches adopted, citing the potential of personal carbon allowances. On the other hand, participant B argued the option could prove socially regressive where policies such as the UK's Feed in Tariff are publically funded via subsidies, but its uptake is restricted to only those with capital to afford the photovoltaic cells.

Offshore wind energy performed moderately with respect to its creation of industry and jobs, but some variability was expressed around its uneven imposition upon people. The option's high energy prices were viewed to be socially regressive. A new market mechanism performed poorly against ethical criteria. It was argued to raise a significant set of ethical questions around the new sets of 'winners' and 'losers' it would create.

Business as usual performed poorly against ethical criteria, albeit with some variability. Participant D noted that the ethics of 'carrying on' were unproblematic, as were those of its 'unintentional' impacts. Participant B stated that whilst business as usual was likely to be reducing global inequalities in absolute terms, there were considerable variations within and between countries. Participant G considered the prioritised interests of business over other considerations, including intergenerational equity, as unacceptable, and ruled the option out on principle.

3.2.8. Co-benefits

This 'other' criterion was appraised in isolation by only participant B, but themes of co-benefits were seen to run throughout the other participants transcripts despite not having been explicitly addressed.

Of the three core geoengineering options, biochar performed most highly against the co-benefit criterion, scoring moderately through its co-benefits to agriculture, namely: improved soil conditioning; increased water retention and related lowered irrigation demands; and increased productivity and yields. Air capture and storage scored very poorly, with no co-benefits identified. In agreement with other research (Hulme, 2012), stratospheric aerosol injection scored very badly, with participant B remarking at its likely 'co-problems' if anything, including a possible contribution to ozone depletion.

Voluntary low carbon living was seen to perform moderately against the co-benefit criterion, with personal benefits cited. Offshore wind energy scored moderately too, with improved energy security and health co-benefits associated with air quality improvements following a departure from fossil fuel energy sources. A new market mechanism was viewed as spouting similar potential health benefits, but scored poorly with little else to offer.

Business as usual scored highly against the co-benefit criterion, with clear social benefits associated with economic growth and poverty reduction.

3.3. Option ranking

Fig. 1 shows the final overall rankings of each participant's appraisal of the seven core options. A number of key findings can be identified, the most obvious being that participant's different perspectives have amounted to different option rankings. Despite these differences, the ranks of geoengineering options are most often lower than those of the mitigation options. There are a few exceptions to this pattern, with the opposite being true for participant I. Important nuances also emerge between the individual options. Of the core geoengineering options, at their best biochar and air capture and storage are often seen to outperform stratospheric aerosol injection, drawing a distinction between carbon and solar geoengineering options. Of the core mitigation options, at their best voluntary low carbon living and offshore wind energy are often seen to outperform a new market mechanism. Business as usual is almost consistently the worst performing option. Interestingly, its performance is not unlike that of stratospheric aerosol injection, reflecting debates recorded in the interviews about their similarities.

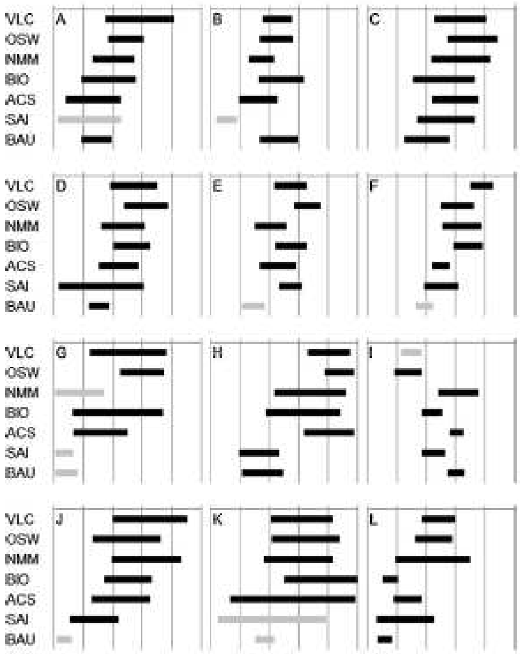

Fig. 1. Final rankings of core options assigned by participants A–L. Acronyms: voluntary low carbon living (VLC); offshore wind energy (OSW); new market mechanism (NMM); biochar (BIO); air capture and storage (ACS); stratospheric aerosol injection (SAI); business as usual (BAU). Notes: performances increase on an arbitrary subjective scale to the right. Bar length represents uncertainty between the mean optimistic and pessimistic performance scores across each participant's criteria. Greyed performance ranges indicate options ruled out against at least one principle.

The uncertainties represented by the ranges between optimistic and pessimistic scores are an important feature of the rankings. Indeed, it can often be seen that better performing options are outperformed under their pessimistic scores by poorer performing options under their optimistic scores. These uncertainty ranges echo the findings of earlier MCM research by Stirling and Mayer (2001), where GM crop options were appraised against non-GM alternatives. Levels of uncertainty varied widely across all options and participants, with some participants expressing more uncertainty with geoengineering options and some more with mitigation options. Uncertainty around business as usual was consistently relatively low, but its different rankings reflect different participant's perspectives as to its relative risks and benefits and of the adaptability of society. Participants representing government (J, K, L) could tentatively be described as having expressed greater uncertainty than the other sectors, contrasting particularly with participant I (industry).

Fig. 1 also shows that three core options were ruled out against at least one principle by at least one participant. In fact, voluntary low carbon living and a new market mechanism were ruled out by 1 participant each; stratospheric aerosol injection was ruled out by 4 participants; and business as usual was ruled out by 5 participants. Table 4 details which options were ruled out, by how many participants, against which principles. Participants who did not rule any options declared that all options needed to be explored, with participant L remarking 'We can't afford to rule any of them out'.

Fig. 2 shows the aggregated final overall rankings of all participants' appraisals of core, discretionary and additional options. Whilst such aggregated rankings should always be

Table 4
Options ruled out against which principles.

Option	Principles ruled out against
C1 Voluntary low carbon living (ruled out by 1 participant: I)	Technical feasibility
C3 New market mechanism (ruled out by 1 participant: G)	Greenhouse gas reduction; environmental side effects; transboundary impacts; socioeconomic impacts; ownership and control
C6 Stratospheric aerosol injection (ruled out by 4 participants: A, B, G, K)	Global temperature reduction; greenhouse gas reduction (2); environmental side effects; transboundary impacts; social acceptability; socioeconomic impacts; governance; political acceptability; distributive justice; ownership and control (2); co-benefits
C7 Business as usual (ruled out by 5 participants: E, F, G, J, K)	Climate change impacts reduction; climatic response time; global temperature reduction; greenhouse gas reduction (2); environmental impacts; environmental side effects; transboundary impacts; cost; human impacts; socioeconomic impacts; intergenerational equity; ownership and control
D5 Iron fertilisation (ruled out by 1 participant: G)	Greenhouse gas reduction; environmental side effects; transboundary impacts; socioeconomic impacts; ownership and control
D7 Space reflectors (ruled out by 1 participant: E)	Cost

Note: (2) indicates a principle was invoked by two separate participants in relation to the corresponding option.

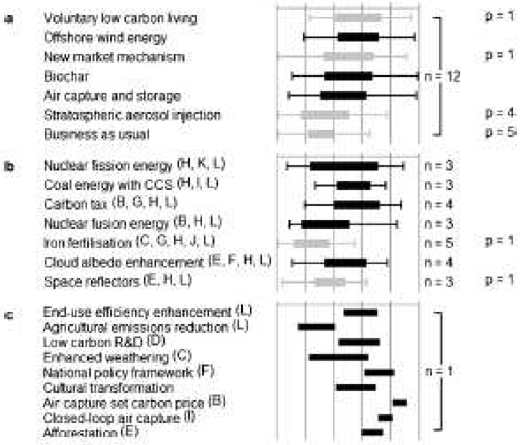

Fig. 2. Aggregate final rankings of core options appraised by all twelve participants (panel a), discretionary options appraised by some participants (panel b, participant codes indicated beside corresponding options) and additional options appraised by individual participants (panel c, participant codes indicated beside corresponding options). Acronyms: carbon capture and storage (CCS); research and development (R&D). Notes: frequency of participants appraising (n) corresponding options and ruling them out on principle (p) indicated to the right of the graphic. Performances increase on an arbitrary subjective scale to the right. Bar length represents uncertainty between the grand mean of optimistic and pessimistic performance scores. Range 'error' bars represent extreme maximum and minimum mean optimistic and pessimistic scores. Greyed performance ranges indicate options ruled out against at least one principle by at least one participant. Note that options ranks on panels b and c are not on the same scale as panel a, nor are they on the same scale as one another due to different participants and participant frequencies. The relative positions of these ranking intervals are therefore much less robust than for the core options in panel a, and should be interpreted with caution.

interpreted with caution, the figure includes 'error' bars to represent the extreme optimistic and pessimistic final overall scores of individual participants, to ensure that the full range of uncertainty is represented. Indeed, panel (a) shows the uncertainty to stretch almost the full length of the performance scale for many of the core options. The aggregated scores reaffirm the findings of the individual final overall appraisals discussed above and shall not be repeated here. It should be noted, however, that option ranks on panels b and c are not on the same scale as panel a, nor are they on the same scale as one another due to different participants and participant frequencies. They should therefore be interpreted with more caution.

Of the discretionary options (Fig. 2b), mitigation options can again be seen to outperform their geoengineering counterparts. Of the discretionary geoengineering options, at its most optimistic cloud albedo enhancement was seen to outperform space reflectors and iron fertilisation. Iron fertilisation was ruled out on principle by participant G for its questionable efficacy, risk of unintended environmental impacts, socioeconomic impacts, transboundary effects and privatised control. Space reflectors were ruled out on principle by participant E for their prohibitive financial cost. Of the discretionary mitigation options, at its most optimistic a carbon tax outperformed coal energy with carbon capture and storage and nuclear fission energy. Nuclear fission energy bore the most uncertainty, reflecting debates raised across the criteria. Nuclear fusion energy performed least well at its most optimistic, reflecting participants' pessimism over its development time or simply its viability.

Additional options (Fig. 2c) were appraised by the individual participants that proposed them, often having been introduced as their favoured options. Indeed, five of these went on to outperform all other options being appraised by their proponent. These were cultural transformation (B); afforestation (E); air capture set carbon price and air capture with closed-loop utilisation (I); and end-use efficiency enhancement (L).

3.4. Implications for geoengineering governance and appraisal

This section further discusses the analysis with respect to the implications for geoengineering technologies, governance and appraisal, drawing on the reflections of the participants and with reference to the wider literature.

3.4.1. Geoengineering technologies 'in context'

There was strong agreement amongst participants that mitigation options should always be given priority over geoengineering proposals, which were viewed by participant C as an insurance policy. More precisely, carbon geoengineering proposals were seen as more acceptable than their solar counterparts, being potentially useful in offsetting emissions that proved difficult to mitigate against. The solar proposals were viewed by participant J only as a response to climatic emergencies such as those that might arise from climate tipping points. However, these generalised observations were joined by the fact that individual geoengineering proposals bore very little in common with one another and that the carbon-solar dichotomy, as well as the even more aggregated umbrella term 'geoengineering' was unhelpful. Such findings resonate with recent calls to disaggregate the term (Heyward, 2013; Boucher et al., submitted for publication).

3.4.2. Governance on a case-by-case basis

It was noted by all participants that no single regulatory framework would effectively govern the disparate suite of proposals that had been forced under the 'geoengineering' umbrella. Indeed, disaggregating the governance needs of the different proposals was described by participant D as '. . .going to be messy and complicated with a lot of twists and turns'. Participant B affirmed that the proposals would need to be governed on a case by case basis, remarking 'I can't offer a nice, neat set of principles'. It was noted that in many cases, established geoengineering proposals such as afforestation could be covered by existing governance structures. Participant C suggested that other existing governance structures could be modified and extended to cover other proposals, such as is the case with iron fertilisation and the London Convention (IMO, 2007). Such broadly optimistic views resonate with Humphrey's (2011) whilst contrasting with the more cautious Virgoe (2009). On the other hand, more difficult and novel governance issues were noted to arise from solar geoengineering proposals, in particular stratospheric aerosol injection (see also Macnaghten and Szerszynski, 2013). Transboundary effects and geopolitical relations were seen to be key points of contestation. Existing geoengineering governance projects such as the SRMGI (SRMGI, 2011) and the Oxford Principles (Rayner et al., 2013) were said to be 'pushing in the right direction' (D).

3.4.3. Experimentation, demonstration and anticipation

Participants E and I both expressed their beliefs that geoengineering field trials would be likely in coming years. Both referenced the recent and controversial iron fertilisation experiments conducted by Canadian scientist Russ George (Lukacs, 2012), suggesting that trials of stratospheric aerosol injection would soon follow. Indeed, participant I even suggested that such trials could take place in the US by the mid 2020s, perhaps in response to extreme weather events, with other nations likely to follow suit. Whilst participant I remarked that effective governance arrangements were unlikely to be ready in time for such trials, participant E suggested that there would be swift moves to resist them. Participant L communicated the essential need for geoengineering governance structures to be in place before full-scale deployment was considered, and preferable need even before small-scale field trials. These comments echo the call for 'governance before deployment' in the Oxford Principles (Rayner et al., 2013).

3.4.4. Multilateralism, unilateralism and scale

A dichotomy of governance implications emerged around those geoengineering proposals that would operate locally within nation states and those that would operate globally and internationally. The former group of proposals were considered to be largely unproblematic, falling under the jurisdiction of territorial governance regimes. The latter group of proposals, however, were viewed as requiring multilateral agreement sought through a global institution, most likely the United Nations (UN), echoing research by Virgoe (2009). Several participants noted the irony of this pursuit, with participant L remarking: 'it could take as long as the climate negotiations themselves'. Negotiating the terms of such an agreement, such as what temperature to set the 'global thermostat' were seen as intractable issues. Whilst participants noted that multilateral agreement should be sought for those geoengineering proposals with global, international implications, the risk of unilateral or consortia-led deployment remained. Stratospheric aerosol injection was of particular concern in this regard: 'We keep moving very quickly towards the SRM [Solar Radiation Management] conversation, because that's where the danger is' (F). The geopolitical tensions that could arise from such an endeavour were considered a matter of acute concern.

3.4.5. Inclusion, reflexivity and appraisal

Participant A emphasised the need for engaging publics in decision making on geoengineering, expressing its need to be open, democratic and accountable. They furthered the notion of reflexive governance, of the need for cautious and continuous appraisal, including beyond its eventual deployment should it happen. Such sentiments resonate with the objectives of real-time technology assessment and anticipatory governance (Guston and Sarewitz, 2002); of which reflexive appraisals processes such as MCM can form an important part. On this final point, in reflecting on their experience of the MCM study, all of the specialists and stakeholders remarked at the heuristic utility of MCM in mapping the extensive scope of issues raised by geoengineering. Indeed, the resultant complexity was considered 'difficult' to engage with by four participants. On the other hand, three others found the process 'logical' and 'straightforward'. The systematic rigour of the process, its flexibility to different participants' engagements and its openness to diverse framings and perspectives were all cited as strengths.

4. Conclusions and recommendations

In this study we have begun to address the limitations that have beset other appraisals of geoengineering by 'opening up' appraisal inputs and outputs to a wider diversity of legitimate framings, knowledges and future pathways that exist. In doing so a number of our findings contrast with those of other published appraisals which have adopted narrower inputs and closed down the outputs. In particular, where stratospheric aerosol injection has previously outperformed other geoengineering options, by opening up to a broader diversity of criteria (spanning all the identified criteria groups) and other options for tackling climate change it has been shown to perform relatively poorly. Under the broader framing conditions adopted in this study a further key finding is that geoengineering options most often performed less well compared to more established options for mitigating climate change (including voluntary low carbon living and offshore wind energy). As would be expected, these findings and the performance of all options are subject to varying degrees of uncertainty, something that is actively explored and transparently presented by the MCM approach.

In light of our findings, we propose three recommendations for policy and future research. First, no one option for tackling climate change is a panacea and policy should reflect the diversity of options and possible pathways at different scales. Second, our analysis illustrates that the term 'geoengineering' comprises a range of disparate technology proposals which have distinct qualities and performance ranges. This could be taken as support for calls to disaggregate the term and for geoengineering proposals to be governed on a case-by-case basis. There is certainly a need to discriminate between different proposals, their innovation contexts, and the imagined futures they invoke. Yet, the approach that we have developed in this paper cautions against moves to consider geoengineering proposals in isolation. Such practice would marginalise vital comparative dimensions and serve to close down the decision context. The key is to open up the framing of appraisals to consider geoengineering proposals in comparative context and avoid premature 'lock-in' to particular options or pathways. For those geoengineering proposals and appraisals that remain narrowly or technically framed the challenge is to reflexively consider the closing effects of their framing conditions (problem definitions, options, criteria, knowledge inputs, and so on) in a more open and transparent way.

Our third and final recommendation is that reflexive appraisal approaches such as MCM form an essential part of ambitions to realise wider frameworks of responsible innovation for geoengineering that encourage anticipatory, reflexive, inclusive and responsive forms of governing in the face of radical uncertainties/indeterminacies, competing visions and social concerns (Owen et al., 2013; Stilgoe et al., 2013; Macnaghten and Chilvers, 2013). Recent controversies relating to geoengineering experiments such as the UK's SPICE project (Macnaghten and Owen, 2011), the LOHAFEX (Iron Fertilisation Experiment) trial (Strong et al., 2009) and the 'rogue' iron fertilisation of the Haida Salmon Restoration Corporation (Tollefson, 2012) stress the importance of the sort of *anticipatory* appraisal conducted in our research. The MCM process has been *reflexive* in the way it created spaces for scientists and stakeholders to openly reflect on and learn about their own framing conditions, assumptions, and the social, ethical and political implications of geoengineering technologies in a transparent way. While our approach has been *inclusive* in terms of specialist and interest group representation, it also provides opportunities to build on existing work exploring public deliberation on geoengineering technologies per se (e.g. Pidgeon et al., 2013; Macnaghten and Szerszynski, 2013) by opening up to broader framings using MCM's sister-methodology of Deliberative Mapping (see Davies et al., 2003; Burgess et al., 2007; Chilvers and Burgess, 2008). The potential for reflexive appraisal approaches such as these to enhance the *responsiveness* of geoengineering governance depends on their connections with wider governance systems of which they are part. Such procedural techniques ultimately only form part of a diverse set of ways in which the reflexive and responsive capacities of actors and institutions implicated in governing geoengineering and climate change should be prompted and enhanced in collective-experimental, relational and ongoing ways (Wynne, 1993; Stirling, 2006; Chilvers, 2013; Stilgoe et al., 2013).

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Appendix 3.3 Framing geoengineering assessment (in Geoengineering Our Climate Working Paper and Opinion Article Series; reused here with permission)

Geoengineering
Our Climate?

Ethics, Politics and
Governance

Opinion Article
10 December, 2013
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Framing Geoengineering Assessment

Rob Bellamy
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Geoengineering Our Climate? is a Working Paper and Opinion Article Series that explores the ethics, politics and governance of geoengineering – the intentional manipulation of the global climate to counteract climatic changes. Relying upon the efforts of over forty contributing authors from academia, policy, and civic environmentalism, our objective for this project is to create a comprehensive yet broadly accessible introduction to the complex societal dimensions associated with the emergence of geoengineering. Our Convening Partner organizations include high-profile institutes from across the global north and south: the Institute for Advanced Sustainability Studies (Germany); the Institute for Science, Innovation and Society, University of Oxford (UK); the Consortium on Science Policy and Outcomes at Arizona State University (US); the Council on Energy, Environment and Water (India), the Research Centre for Sustainable Development of the Chinese Academy of Social Sciences (China), and the Brazilian Research Group on International Relations and Climate Change (Brazil).

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Citation Information

Bellamy, R. 2013. "Framing Geoengineering Assessment." Opinion Article, Geoengineering Our Climate Working Paper and Opinion Article Series. Available at: http://wp.me/p2zsRk-9H

The ways in which social actors choose to organise and communicate, or 'frame', ideas such as geoengineering channel expressions of power. In support of decision making, the selection of contexts and methods in technology assessment both constitute broad sites of instrumental framing, which act to condition assessment outcomes.[1] As an 'upstream'[2] suite of technology proposals that is currently in advance of significant research and development or public controversy, geoengineering is particularly sensitive to these, and other, framings.

Assessments of geoengineering have so far largely taken place under two dominant problem definitions.[3] First, that efforts to reduce greenhouse gas emissions will not be enough to tackle climate change ('insufficient mitigation'). Second, that as a result of this, we may be faced with a dangerous change in climate, often stylised as crossing one or more 'tipping points' (a 'climate emergency'). Both of these framings posit a central role for geoengineering in tackling climate change, concurrently marginalising legitimate alternatives. Accordingly, geoengineering assessments have largely excluded mitigation options and adaptation, placing the proposals in what can be termed 'contextual isolation'.

Although geoengineering framings have begun to emerge and diversify in the media[4] (with coverage likely to increase following its heightened prominence within the Fifth Assessment Report of the Intergovernmental Panel on Climate Change), it typically remains a scientifically and technically framed issue within the assessment literature.[5] Most of the assessments use technical and analytic methods that are exclusive to experts (such as climate models or cost-benefit analysis), and narrowly-focused, technical criteria (such as global temperature reduction, rapidity of effect and cost). Under such methods and criteria certain issues are privileged, and so too are certain proposals. It is perhaps no surprise then that an ostensibly effective, fast-acting and cheap proposal, stratospheric aerosol injection, often performs very highly[6] and is gaining attention.

The expert multi-criteria assessment conducted for the Royal Society's (2009) seminal report provides a valuable illustration of how framing geoengineering assessment through the selection and elevation of particular criteria can compel particular outcomes. The assessment utilised four technical criteria with which to evaluate the proposals: effectiveness, affordability, timeliness and safety. In then presenting the performances of the different proposals on a two axis figure, a difficult decision was made with respect to which of the four criteria would be given priority on those axes. It was decided that effectiveness and affordability would be given that normative priority, and under that configuration stratospheric aerosol injection performed the highest overall.

The prioritisation of effectiveness and affordability on those axes, however, was only one of a possible six permutations (Figure 1). Each of the differently framed permutations offers a distinct pattern of performances, where different overall conclusions can be

[1] Stirling, 2008
[2] Wilsdon and Willis, 2004
[3] Bellamy et al, 2012
[4] Porter and Hulme, 2013; Scholte et al, 2013
[5] Bellamy et al, 2012
[6] Lenton and Vaughan, 2009; Royal Society, 2009; Bickel and Lane, 2009

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drawn. Where the original configuration places stratospheric aerosol injection most highly (a), that performance is accentuated even further under effectiveness and timeliness criteria (b), owing to its perceived capacity for pre-emptive or responsive action in facing a sudden 'climate emergency'. Where safety is prioritised alongside effectiveness a somewhat different picture emerges (c), with air capture and storage performing the highest overall. Under affordability and timeliness criteria, stratospheric aerosol injection returns to a high performance, but alongside the somewhat more benign afforestation (d). Afforestation retains the coveted position of highest overall performance under affordability and safety, and timeliness and safety criteria (e, f).

These permutations demonstrate how different instrumental framings can serve to 'close down' on certain geoengineering proposals.[7] Such closure leads to prescriptive policy recommendations that promote further research and investment in proposals that seem preferable given the narrow framings upon which they are built. This poses the risk of premature 'lock-in'[8] to particular future pathways that could instigate conflict and controversy between divergent values and interests. Geoengineering assessments should instead seek to 'open up' option and policy choice by adopting broader and more diverse framings in order to guard against this lock-in.[9] Rather than providing prescriptive policy recommendations, the assessments would provide conditional recommendations that expose the framing conditions under which options perform.

[7] Stirling, 2008; Bellamy et al, 2012
[8] Arthur, 1989
[9] Stirling, 2008

The primarily narrow and technical problem definitions and criteria deployed in geoengineering assessments have recently prompted the use of a different kind of expert-analytic method; one that seeks to open up those, and other, inputs. Using a Multi-Criteria Mapping methodology[10] and in defining the 'problem' as one of responding to climate change in its broadest sense, rather than in narrowly responding to insufficient mitigation or a climate emergency, a diversity of alternative options and criteria has been yielded.[11] Both the range and depth of criteria has been diversified, under which a radically different picture of option performance emerges. The range of criteria groups has been opened up beyond 'technical' issues to include those of 'social' ones spanning politics, society, ethics and co-benefits to show that geoengineering proposals, and stratospheric aerosol injection more acutely, are outperformed by mitigation alternatives. Moreover, the depth of criteria groups has been opened up within those 'social' issues as well as the more 'technical' issues of efficacy, environment, feasibility and economics, to show the same pattern.

In seeking to open up the assessment of geoengineering further still, a small but significant literature in public participation has begun to emerge. The outcomes from participatory assessments (such as surveys or focus groups), however, are also susceptible to instrumental framing. The 'climate emergency' framing has proven particularly potent in such settings, underpinning apparent public support for research into solar geoengineering in a cross-cultural survey[12], and likely improving the perceived public acceptability of

[10] Stirling and Mayer, 2001
[11] Bellamy et al, 2013
[12] Mercer et al, 2011

solar geoengineering in the UK-based Experiment Earth? public dialogue. A 'naturalness' framing was also likely to have improved the perceived acceptability of particular geoengineering proposals in that same public dialogue.[13] Framing air capture and storage as 'artificial trees' and stratospheric aerosol injection as 'no different to a volcano', for example, might constitute valid technical descriptions, but can also frame particular ends. Nevertheless, the naturalness framing has also emerged unprompted from publics themselves as an important element in forming their perceptions of geoengineering.[14]

Broadening out and opening up geoengineering assessment reveals the complexities and uncertainties that are often reduced and hidden in narrowly framed assessments. For policy makers, this might make uneasy reading. Opening up assessment in these ways may appear to make decision making harder rather than easier. However, this need not be the case. Neither expert-analytic nor participatory assessment methods are complete without the other, and so methods have been designed that integrate both elements. Deliberative Mapping is one such method that we have recently developed and used[15], in combination with Multi-Criteria Mapping[16], to evaluate geoengineering proposals alongside other options for tackling climate change. Whilst the method seeks to map divergence of perspectives, it can equally map consistencies. Indeed, a remarkable level of consistency has been found across expert, stakeholder and public perspectives, with geoengineering proposals being outperformed by mitigation alternatives.

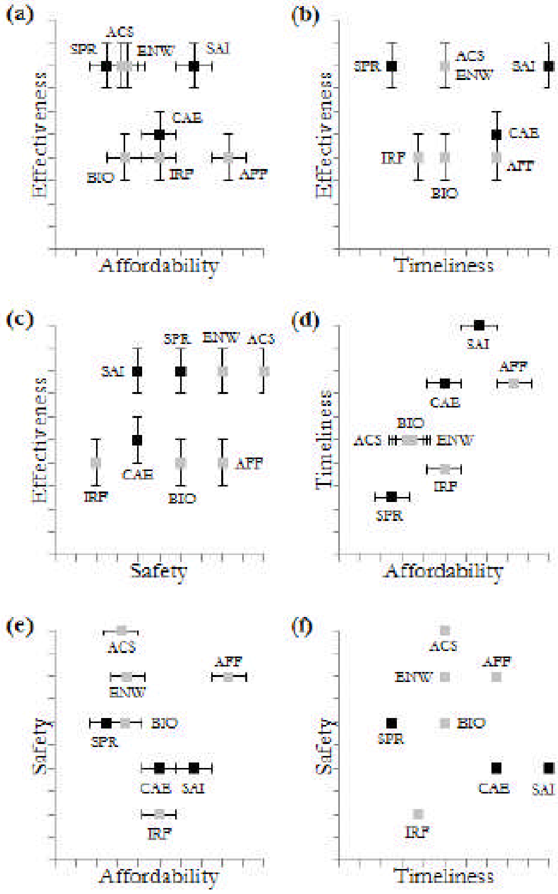
We can draw a number of lessons for future research and policy from attempts at framing geoengineering assessment. Firstly, the contextual isolation into which geoengineering has been placed must be overcome, by replacing narrow problem definitions such as being faced with a 'climate emergency', with broader ones such as 'responding to climate change'. This introduces alternative options spanning mitigation and adaptation that cannot be ignored. Secondly, the use of narrow, technical criteria must overcome by expanding the range and depth of 'social' as well as 'technical' criteria. This second lesson must be supported by a third, in which the prevailing use of expert-analytic methods of assessment must be supplemented by, or integrated with, (carefully-framed) participatory methods that include a diversity of stakeholders and publics. This diversity will help hedge against the risk of 'lock-in' to particular proposals that may at first appear preferable under certain framings. Taken together, these lessons argue that the framing of geoengineering assessments should be broadened out and opened up.[17] Indeed, as this article has shown, some initial efforts have already been made in acting on these lessons but much more remains to be done.

[13] NERC, 2010; Corner et al, 2011
[14] Corner et al, 2013
[15] Bellamy et al, under review
[16] Bellamy et al, 2013

[17] Stirling, 2008; Bellamy et al, 2012

3

Figure 1.
Permutations in a multi-criteria assessment of geoengineering proposals.



Acronyms: afforestation (AFF); air capture and storage (ACS); biochar (BIO); cloud albedo enhancement (CAE); enhanced weathering (ENW); iron fertilisation (IRF); stratospheric aerosol injection (SAI); space reflectors (SPR). Proposals coloured grey and black represent carbon geoengineering and solar geoengineering proposals respectively. This figure was produced using the original performance scores and margins of error for select proposals provided in the Royal Society (2009).

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