The Stabilisation of Geoengineering:

Stabilising the Inherently Unstable?

Peter Healey

Climate Geoengineering Governance Working Paper Series: 015.

Published online 12 November 2014

Climate Geoengineering Governance (CCG)

Climate Geoengineering Governance (http://geoengineering-governance-research.org) is a research project which aims to provide a timely basis for the governance of geoengineering through robust research on the ethical, legal, social and political implications of a range of geoengineering approaches. It is funded by the Economic and Social Research Council (ESRC) and the Arts and Humanities Research Council (AHRC) - grant ES/J007730/1

CGG Working Papers

The CGG Working Paper series is designed to give a first public airing to a wide range of papers broadly related to the project's themes. Papers published in this series may be, but are not necessarily, early outputs from the project team; equally they may be from other authors, and reflect different perspectives and different issues from those directly pursued by the project itself. The aim is to promote vigorous and informed debate, in a spirit of pluralism.

What the working papers have in common is that they will all be at an early stage of development, prior to full publication. Comment and response, at any level of detail, is therefore doubly welcome. Please send all responses in the first instance to the authors themselves - each paper contains a correspondence address. We will be looking for opportunities to use the website or other project activities to give a wider airing to any dialogues and debates that develop around a paper or issue.

About the Author

Peter Healey (peter.healey@insis.ox.ac.uk) is Research Fellow in the Institute of Science, Innovation and Society, University of Oxford, and co-ordinator of the CGG project. His interests have been in scientific governance, especially in relation to democratisation, S&T indicators, and international and distributional aspects of S&T. More recently his interests have turned to the implications of two converging epi-phenomena of globalisation: the rapid diffusion of new technologies, and the emergence of new powers; their joint potential to bring new agendas to the fore in international governance of science, technology and innovation; and the implications of these changing dynamics for economic, politico-military and environmental security at a world, regional and global level.

The Stabilisation of Geoengineering: Stabilising the Inherently Unstable?

Peter Healey

Institute of Science, Innovation and Society (InSIS), University of Oxford

Abstract

This paper examines whether and on what terms geoengineering - the deliberate large-scale employment of a variety of technical practices designed to counter man-made climate change - may become stabilised as a technology, and the consequences of its failure to achieve this.

Two features can be said to mark the stabilisation of a new technology: first its ability to define itself in term of the core-set of those people constituting the field, and the epistemological approach and core technical practices which they employ and which distinguish the technology from others; and, second, its ability to go beyond the core-set of pioneers to establish the potential benefits of the technology amongst a wider global network possessing important resources for the technology's development. These resources include legitimacy amongst potential sponsors and users (states, corporates, citizens and consumers) and access to research funding for development, detailed assessment, and delineation of technology-specific issues of governance and regulation.

The paper suggests that geoengineering lacks a number of features that have led to the stabilisation and large scale research funding of earlier technologies of control: molecular biology, biotechnology and nanotechnology. As a result geoengineering is unlikely to be carried forward as a unitary enterprise; instead its many varieties can best be thought of as just part of the range of socio-technical options for responding to climate change, as well as potentially delivering a range of

co-benefits for food, energy and water. Re-positioning geoengineering discourse in this rather more modest way is seen to contribute increased analytical rigour to the assessment of geoengineering, mitigation and adaptation, in addition to reducing the policy barriers to the consideration of geoengineering's possible contributions.

Acknowledgments

This paper has benefited from helpful comments from Steve Rayner, Javier Lezaun and Clare Heyward.

Introduction

Geoengineering, otherwise known as climate engineering, is a very diverse set of mostly immature technological practices, which seek to modify the earth's climate by the use of large scale engineering approaches applied in the oceans, on land, or in the upper atmosphere or in space. Given this diversity of approaches within geoengineering, and the high degree of uncertainty regarding the effectiveness of geoengineering techniques and the extent to which they will have unintended consequences, it is an important and relevant question as to whether geoengineering can, in a unified way, achieve, and then maintain, stabilisation. Stabilisation is important to geoengineering, as to any emerging technology, because it brings a global network to 'generate, for a period of time, a set of resources in which innovation can take place' (Law & Callon, 1992, p.21): because it can open the door to early imaginaries of possible use, which in turn may generate (conditional) legitimacy amongst potential sponsors and users (states, corporates, citizens and consumers) and access to research funding for development, detailed assessment, and delineation of technology-specific issues of governance and regulation. As we will see, nanotechnology is a paradigm case which achieved all of these. It is currently far from clear that geoengineering will be in a position to do likewise. If geoengineering does not achieve and maintain stabilisation as a unitary enterprise, but instead fragments into its component approaches, it may attract less funding, questions about efficacy and safety may continue to be unresolved, and its options may not be seriously fully considered against other approaches to managing climate change, with a potential reduction in the range of possible policy options.

In science, technology and innovation, stabilisation can be thought of as that process of socio-technical consolidation which allows broad recognition of the key defining features of an emerging technology, including a definition of its key technical practices and/or epistemological commitments. Stabilisation also delineates a core set of actors, and indeed does so as a result of their strategies to promote their field. These strategies bring heterogeneous social and technical resources together under a marketable proposition which helps to legitimise the field, educate key stakeholders and wider publics as to the opportunities which it claims to bring, and through this command wider resources.   Such strategies most often arise from within a group of scientists and technologists, but also can arise from outside these communities; in any case they need to command legitimacy in both.

Stabilisation can thus be conceived as a temporal, technological and social boundary setting exercise, creating spaces for action, spaces in which the commercial, scientific, civil society and governmental interests may interact in attempts to promote and govern a technology in a variety of settings. In this sense stabilisation might be thought of a broad "initial (sociotechnical) public offer" – positioning a broad new field in relation to a wide range of interests, in an analogous way to the commercial IPO of an individual new company. Because of these competing interests however, any stabilisation is a fragile and dynamic construct, always subject to contestation and negotiation, from within the field or from encounters with various publics (Bauer & Wahlberg, 2009, p.4). Furthermore, stabilisation may not be a unitary concept: as we will explore later Mol (2003) has pointed to the multiple, nested, almost recursive nature of stabilisations in clinical settings.

This paper has four parts. First it tries to situate and elaborate the process of stabilisation conceptually in relation to how it identifies, frames and mobilises, in relation to imaginaries and lock-in, and in relation to the distribution of risks and opportunities seen to be posed by new technologies. Secondly, it then briefly reviews a number of empirical cases of sociotechnical stabilisation sharing a strand of intellectual history

- molecular biology, biotechnology and nanotechnology. These cases help to clarify the concept and point up some of the key features of stabilisation and the main processes at work, in particular examining the role of individual and institutional agency in developing a definition of the field, and resources of legitimacy and finance to allow it to go forward. Thirdly, it uses this background to analyse the case of geoengineering to examine the extent to which it may have achieved stabilisation and its prospects for doing so as a unitary enterprise, based on a comparison with medicine. Finally it adopts a normative voice in thinking through some of the implications for how geoengineering might be analysed and governed.

1. Situating stabilisation:

This section of the paper tries to locate stabilisation in relation to its constitutive processes and structures, and in relation to the literature on imaginaries, and on lock-in. It asks what is distinctive about stabilisation, and what structures and processes help to maintain or fragment it.

Structure and Process in Stabilisation

Bijker and Law (1992, p.10), in summarising the case studies they bring together in their volume, see stabilisation in these terms:

> "a technology is stabilized if and only if the heterogeneous relations in which it is implicated, and of which it forms a part, are themselves stabilized. In general, then, if technologies are stabilized - together with the various strategies which drive and give shape to the network - are themselves stabilized".

A minimum requirement in stabilising a new technological innovation must be establishing its boundaries - what and who counts as being inside and outside. This might be done through establishing a *socio-technical frame* (Law and Bijker 1992) - " a combination of the explicit theory, tacit knowledge, general engineering practice, cultural values, prescribed testing procedures, devices, material networks and systems used in a community". This frame, we may suppose, will never be entirely consensual or prescriptive, certainly not in the early stages of an emerging technology when much will still be contested and the technology cannot yet to be said to represent the "congealed social relations" of its mature form [Cooper and Woolgar,1994), but may employ the interpretative flexibility of *boundary objects,* those objects that are common to several communities of practice which are brought together in the newly stabilised field. Boundary objects, which can be either abstract or concrete, "are...both plastic enough to adapt to the needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites." (Bowker and Star 1999, p.297)

For example, Law and Callon, in their study of a failed British military aircraft project, emphasise the value to the *local network* embodying the project's sociotechnical aims and resources positioning themselves in a wider *global network* "in order to obtain the time and resources needed to maintain [the] local network." Enrolment proceeds from the bottom-up: the resulting *negotiating space* provides "a space, a period of time, and a set of resources in which innovation may take place". In this view of science as political battleground the scientific text itself needs to be enrolled and to reflect the diversity of resources that need to be assembled in the global network:

> "the text [of any article, through its narrative and citations] both constitutes and indexes a mixture of 'scientific', 'social', 'economic' and 'organisational' forces" (Law, 1986, p. 79)

In the terms of the dynamics of an emerging technology, we can see Bijker and Law's strong definition of stabilisation as applying to a relatively late, mature stage of development. This is consistent with the extensive work in which a stabilised network is seen by them as performing, presenting "a geography of enablement and constraint" - that is, a situation in which some opportunities have already been 'closed down' (Stirling, 2005) with the consequence that those involved find some paths of development easier to follow than others (this is taken up in the discussion of lock-in below).

In two strands of theory in science and technology studies, actor-network-theory and social constructivism, the networks are heterogeneous, comprising humans, objects and systems, which stretch across the technical, political, economic and business communities which need to be enrolled for the network to achieve its strategic objectives. Politics, at many levels and scales, is always present. We can describe such a process of research led stabilisation as a form of social epistemology[1]: they describe the full scope of sociotechnical processes that need to be gone through if the technology is to be implemented in a socially and economically sustainable manner.

---

[1] Latour (2005) uses the term 'political epistemology'.

[2] My emphasis

There is, however a puzzle here. Do all forms of stabilisation, in the more restricted 'initial public offer' sense with which we framed this paper, conform in every aspect to this type? Research-led emergent fields in the process of initial stabilisation are of course in the business of making substantive claims for products and processes that will result from their approach. At their most ambitious, as in nanotechnology, they may be all-encompassing: the ability to make anything, virtually anywhere, for very little. What about technically diverse fields which may lack a core epistemology but which derive their identity from the claims they make to contribute to an applied social purposes like medicine, defence, or climate change. Do such broad social purposes by themselves have sufficient power as boundary objects to hold an emerging field together? If not, should we think of stabilisation operating in a different way in such contexts, or conclude that such fields are unlikely to maintain stabilisation, even if they initially achieve it?

Imaginaries, stabilisation and lock-in

We can also situate stabilisation in relation to two other processes of socio-political consolidation of science and technology which have a stronger presence in the science and technology studies (STS) literature; imaginaries, and lock-in and path dependence. Imaginaries are part of the process of recruitment of support for a new technology; envisaging what is possible in terms which invoke other national goals and narratives. Lock-in and path-dependence occur when the support network is in place, and has consolidated its position to an extent which severely limits any socio-political alternatives.

Jasanoff and Kim (2009) introduce the notion of *socio-technical imaginaries* as an analytical construct to help to counteract what they see as a lack of theorisation of power in STS. Their case compares different conceptions in the US and South Korea of nuclear power– a technology which might be expected to be dominated by state narratives of control and appropriate use. They are thus concerned with the influence of *national*[2] sociotechnical imaginaries which they define as "collectively imagined forms of social life and social order reflected in the design and

[2] My emphasis

fulfilment of nation-specific scientific and/or technological projects. Imaginaries…at once describe attainable futures and prescribe futures that ought to be attained." They are a means by which S&T projects "encode and reinforce particular conceptions of what a nation stands for" and help select priorities and participants in science policy.[3]

The important power of the concept as Jasanoff and Kim use it is in its temporal and cultural linkage: the power of a broad national narrative which provides continuity between established forms of social order and proposed new technological commitments. The analytic use of the imaginary in Jasanoff and Kim's article is to provide a basis for understanding the historical divergences in two countries perspectives and choices on the same technology; the political use of the imaginary in science policy is to articulate broad and distinctive sociotechnical visions. Indeed, if we characterise technology as sociotechnical system, we might say that no two technologies in different political settings - nuclear power in Jasanoff and Kim's case - are ever identical: they may be similar with regard to some of their constituent artefacts, but different as systems[4].

Others have used the term socio-technical imaginary much more broadly to apply to immature technological concepts that have yet to demonstrate efficacy and safety, and indeed many geoengineering proposals have been described in this way (Heyward & Rayner 2013). Indeed, the construction of boundaries in the course of defining a new sociotechnical field, often has a promissory element to it. In terms of De la Bruzère's (1992) study of the stabilisation of nuclear waste, Law and Bijker comment that "outsiders may find themselves bound not so much by products created within the boundary and exchanged across it, but by the promise of future products" (Law and Bijker, 1992, p. 298). Sociotechnical imaginaries, like stabilisation, embody a future prospectus of products and processes downstream. However, imaginaries only constitute a bid for political, social and financial resources to realise those promises, whilst initial stabilisation represents a funded plan for doing so.

---

3 Jasonoff and Kim op. cit. Imaginaries in this sense have a long history: the founding of the Greenwich Royal Observatory under Charles II had explicitly both disciplinary aims in astronomy and economic ones in the improvement of navigation for trade.

4 This situated perspective contrasts with the essentialist characteristic of geoengineering as a planetary technology as ascribed by Macnaghten and Szerszynski (2013). Discussed further in section 4, below.

In a linear model, *lock-in and path dependence*, might be thought of as features downstream of stabilisation – they are often seen as constituting downstream risks. Collingridge's well known control dilemma (1980) suggests that early on, whilst such risks remain easy to control, they remain largely unknown, whilst by the time they are known lock-in makes them largely ungovernable.

In practice, however some human and capital commitment is essential for any new technology to take off, and in this sense lock-in is "an essential but dangerous facet of complex infrastructural innovation" (Walker, 2000). A sociotechnical imaginary may promote cognitive lock-in (Cairns, 2013), by helping to set the terms of early debate, for both the proponents and detractors of the technology. Ironically both sides in such a debate may be serving one purpose, by focussing attention on one technology, with the implied deselection of others. By the point at which initial stabilisation has been achieved, some of the scope of a field, key actors and approaches, and criteria for assessment, may already have been defined, and all of them may be determined. Whilst not necessarily exhaustive, such early framings may prove very influential, as indeed they are intended to be by the technology's proponents, and serve as a robust product champion. Law and Bijker (1992) use "obduracy" as a term for the product of this stabilisation.

In some cases such obduracy may lead to the development of a stable field with a life of decades. In others it may be that the achievement of initial stabilisation – the moment when a group of technical processes achieve a legitimacy which allows access to funding – is itself also the moment of dissolution, when divergent interests based on differences of technical approach or field of application begin to pull apart what has been a convenient coalition of interests up to that point. Indeed, Bowker (1992, p.71)) in his study of oil exploration patents, suggests that there is a strategic value in maintaining this [negotiating] space "only long enough that social and physical reality will alter" - when the local and global networks have effectively become coterminous, and sociotechnical relations have congealed behind the chosen project.

2 Factors shaping stabilisation: case studies

We have seen that in the theoretical literature stabilisation is seen as a two-stage process by which first, a sufficient stabilisation of discourse is achieved across a *local network* of heterogeneous resources involved in building a sociotechnical project, so as to be able establish project boundaries and set objectives; and second, that network, employing a promissory narrative sometimes linked through the use of a *sociotechnical imaginary* to wider cultural or national tropes, goes on to assemble the *global network* of sociopolitical resources necessary to fulfil the project's aims.

This section of the paper goes on to examine the stabilisation processes of three fields: molecular biology, 'red' and 'green' forms of biotechnology, and nanotechnology and to analyse through some of the detail of this process factors determining how stabilisation is initially achieved, and how it is maintained. These technologies seem appropriate to examine alongside geoengineering because they embody narratives of control of increasing scale or scope.

These three cases unfold successively over a period of time in which there were increased expectations, and changing definitions, of what might broadly be defined as "public consent" for new technologies, fuelled in part by public concerns over technological innovations or practices which were seen to have led to risks to public welfare (Grove White et al., 1997; Jasanoff 1997), and partly by a wish to see science temper its claims (Jasanoff, 2005 and 2007). We will see through the case studies how the global network of sociopolitical resources seen to be necessary to fulfil the technology's aims came to include public consent as one of its essential elements, as perhaps a third final (but highly contingent and therefore not fixed) stage of successful stabilisation.

Molecular biology - individual and institutional agency, "epistemological transfer" and gradual stabilisation

An important issue in stabilisation is individual and institutional agency: the extent to which the crystallisation of a field is seen to brought into being by one or more brokers who combine a synoptic scientific understanding with access to significant resources of legitimacy or finance: for example the roles of Richard Feynman, and later Mikhail Roco and the National Science Foundation in the case of nanotechnology, and, arguably, Paul Crutzen and the Royal Society in the case of geoengineering.

The importance of key brokers in the stabilisation of molecular biology in the 1930s and 1940s has become a contested issue in the history of science and technology. Warren Weaver, a mathematician, had the broad motivation to apply a quantitative approach to the biological sciences – "the physical sciences had by then elaborated a whole battery of analytical and experimental procedures capable of probing into nature with a fineness and quantitative precision that would tremendously supplement the previous tools of biology." The Rockefeller Foundation subsequently invested heavily in equipment for various techniques including X-ray crystallography. Weaver claims to have put forward this vision in his initial job interview with the Rockefeller Foundation, and when appointed it became his base for action. (Weaver 1970, p. 59). In pusuit of this Weaver, who initially adopted the term "quantitative biology" before settling for "molecular biology", a term he first used in the Rockefeller Annual Report for 1938 (Abir-Am, 1982, p. 344), immersed himself in a personal training programme in areas of the biological sciences, starting with genetics, whose significance he saw as central to his mission, had a constant series of visits to universities and laboratories in the United States and Europe, and, perhaps most significantly, had a long correspondence with the chemist Linus Pauling at the California Institute of Technology[5]. This of course was about proposals for support for Pauling's work, but it also showed the development, during the exchange of 23 items of correspondence over nearly 12 years, a mutual understanding of the significance of an emerging field.

Weaver had little doubt of his personal and institutional agency in developing the field during this period. He writes:

> "I believe that the support which the Rockefeller Foundation poured into experimental biology over the quarter century following 1932 was vital in encouraging and accelerating and even in initiating the

[5] the Weaver-Pauling correspondence is at http://scarc.library.oregonstate.edu/coll/pauling/proteins/corr/index.html

> development of molecular biology…between 1932 and my retirement from the Rockefeller Foundation in 1959 the total of the grants made in the experimental biology program which I directed was roughly ninety million dollars.” (Weaver, 1970)

Kohler (1976) largely accepts this view of the importance of Weaver's agency. For Abir Am (1982) individual agency is not enough, the significant transition is from patronage to science policy - power relations making possible certain discourses which in turn sustain certain power relations - so, following Foucault, are new disciplines forged. For her, then, the test is the interaction between the funder's policy and scientific practice - what science at the time established in its perspectives and practices the roots of what became understood as molecular biology by the time of the 1960's, when, post double helix, it had become not only a field of scientific but of cultural discourse[6]?

For Abir-Am (1982), the one programme that Weaver does not cite - Joseph Needham and Conrad H. Waddington's project in physico-chemical morphology at Cambridge University - was the only one that embodied a fully developed conception of molecular biology in the 1930's - that is, a sense of how the new techniques of the physical sciences could be seen as illuminating a biological research agenda. It was also the only one which Weaver did not fund.

Michel Morange, in his *History of Molecular Biology* (1998) largely follows Abir Am. He describes Rockefeller's as a “materialist, reductionist” approach, in line with the ambitions of another physicist, Schrödinger, who was specifically attacked for suggesting an intellectual take-over by physics after a lecture series in which he suggested that the findings of genetics might be explained by quantum physics. Morange contrasts these approaches with that of another physicist, Nils Bohr, whose objective as set out in his Copenhagen lectures of 1932, “was not to make a scientific transfer from physics to biology by applying results from one science to another, but to make an “epistemological transfer”, to try to see how the new vision of the physical world changed perceptions of the biological world.” (Morange, p.72)

---

[6] Abir Am (1982), pp 343

What can we learn about stabilisation from the molecular biology case? Here we have an ambition for the biological sciences labelled, and to some extent, led from without: from funders and practitioners in another field, its adoptive intellectual parent, physics. Primacy of action was with another local network, which funded equipment and personnel which would allow a big advance in physics-based technologies in biological science, including the x-ray crystallography which played its role in the discovery of the double helix. Molecular biology embraced a very wide range of scientific targets and technical practices which only slowly converged; by the time they did so information science was emerging as potentially a stronger a model than physics as a reference point for the field.

Arguably, the promotion by Rockefeller of Bohr's epistemological transfer route could have speeded the emergence of molecular biology as a self conscious organised discipline with a recognised programme and participants; equally, Rockefeller's more intellectually plural provision of toolkits of equipment and trained personnel, was after all not imposed on unwilling scientific participants, and both drew on and contributed to the stabilisation of discourse as to what exactly should constitute the emerging field.

All of this is fully consistent with the analysis expressed in section 1 of this paper, from the work of Callon, Law and Bijker and others, (Bijker and Law, 1992; Callon, Law and Rip 1986) that the work of establishing the boundaries and practices of a new field is performed by the building of a local network which afterwards, in the key stage of stabilisation, develops a global network to widen the resources to advance its ends. Despite this - and this is perhaps the key feature of the case - the notion of Rockefeller's agency in the development of molecular biology, and its employment in a way that exemplifies a transition from science patronage to science policy, seems to survive Abir-Am's analysis. Weaver's ambitions for molecular biology - his personal imaginary for the field - were very broad and emphasised aspects of biological and social control, for example:

> Can man gain an intelligent control of his own power ? can we develop so sound and extensive a genetics that we can hope to breed, un the future, superior men? Can we obtain enough knowledge of physiology and psychobiology of sex so that man can bring this pervasive, highly important, and dangerous aspect of life under control? ….

but after these were criticised he "re-focused his effort on the fundamental: biology and the application of the new techniques of physics to biochemistry, cellular physiology and genetics" (Morange, 1998, p. 81). Rockefeller's funding, by its focused, if limited aims, and broad if discriminant distribution of generous funding, provided the environment for multiple approaches and experiments, which encouraged universities, including Pauling's Caltech, into what were effectively co-funding deals. In applying a Foucault test of 'power relations reshaping power relations' to what constitutes science policy, Abir Am introduced a somewhat deterministic criterion in assessing Rockefeller's contribution: one that expected this actor in molecular biology's global network to be running the show. Abir-Am's conclusion that Rockefeller failed to meet this strong test risks undervaluing the foundation's role in early stabilisation: its undoubted role in developing and stabilising discourse in the emerging molecular biology local network, and in providing wider resources for its growth.

The molecular biology case also underlies the importance of a local network finding a product champion that can not only argue for financial resources, but provide them itself. However, Abir-Am is correct in the sense that molecular biology's substantive roadmap evolved over time, and it was only subsequent to the double helix that it can be said to have stabilised. Nanotechnology, which despite a diversity of scientific practice drawn from engineering , biology and colloidal chemistry could be seen as the physicists' ambition to wrest back the epistemological agenda of the very small from the chemists and biosciences, is part of that roadmap. So is our next case, biotechnology: a field transformed by the power of genetic manipulation which molecular biology had ushered in, and having to face consequential issues of wider public consent which were absent from the history so far.

Biotechnology - progressive stabilisation and international competitiveness

In the sense that the production of beer, wine, bread and vinegar and other products of fermentation have been known since ancient times, biotechnology has long been stabilised. This we can call biotechnology 1. Biotechnology 2 - in the sense of the purposive manipulation and development of natural organisms for the large-scale industrial production of medicines, food and industrial catalysts, has a direct foundation in molecular biology and dates from the discovery and development of penicillin in the middle of the last century and the stream of antibiotics that followed.

These innovations, though novel, had the advantage of pre-existing research, industrial and distribution facilities in medicine, agriculture and chemistry to take up, develop and use their products. In the case of penicillin, demand was heightened by the second world war, and the developers of Fleming's discovery in Britain travelled to the U.S. in 1941 in order to persuade the U.S. Department of Agriculture in Peoria, Illinois and a consortium of American pharmaceutical companies to move the discovery to production (Demain & Fang, 2000). The local network had little difficulty mobilising this existing global network for its ends.

In the next thirty years this biotechnology 2 combined knowledge of molecular biology with increasingly sophisticated process engineering techniques to mass produce a wide range of products, primarily for medicine and agriculture, from cell cultures. This included improved pesticides, herbicides and fertiliser whose use, together with seed varieties improved through conventional cross- breeding techniques, and improved agricultural advice and management, resulted in the so-called "green revolution".

The epistemological gear-change to a third level, biotechnology 3, came with the exploitation of the double helix discovery to manipulate the cell's inheritance mechanisms, creating recombinant DNA technology. This was a step-change in the capacity to innovate and control. The first complete synthesis of a gene in 1970 was followed in 1973 by the first horizontal gene transfer with bacteria and by 1976 genetic engineering had become fully established, leading to key medical products like insulin and human growth hormone being synthesised by foreign genes being introduced into *E. coli.* (Fiechter, 2000b).

It might appear that biotechnology is a straightforward case of progressive stabilisation. Both the transition from biotechnology 1 to biotechnology 2, and the slower change from biotechnology 2 to 3 (in which older processes were never entirely superseded), involved institutional continuity in research funding, production and marketing capacities which were serving mature markets for medical and agricultural products. This institutional continuity provided a social buffering capacity, an ability to mediate the period of epistemological, technical and product change, as well to provide the necessary financial capital for it. This in turn limited the need for any major new forms of individual or institutional agency in sponsorship of the "next industrial revolution." The hyped promise of this revolution arrived just in time to buffer the early shock of the first OPEC oil embargo (1973) and the wider critique of resource exhaustion in *Limits to Growth* (Meadows et al 1972).

However, the history of stabilisation of biotechnology 3 varied across those leading biotechnology innovation, its individual national variants reflecting local imaginaries, institutional histories and perceived competitive advantage. To some extent, the promised power of biotechnology 3 provided the hype behind which more conventional biotechnology 2 programmes were being promoted. In the United States, the power of such an imaginary in biotechnology is demonstrated by a relatively small Research Applied to National Needs (RANN) programme, launch in 1971. This included the prioritisation of enzyme technology (biotechnology 2) which sponsored key research in an area in which US industry still led:

> "...the existence of the RANN program and the contemporary investments by industry promoted a vision of the multiple applications of enzymes in health, agriculture, the environment and industry. RANN's meetings and papers helped develop and publicise models of the central role of enzymes that would look very familar a decade later." (Bud, 1994, p 144).

Bud sees both Japan and Germany as having sold biotechnology on the twin promises of industrial renewal and securing what he calls "environmental balance" - in the Japanese case trying to remediate a poor post-war record of industrial pollution. The life sciences were a policy category in Japan, in contrast to the US, and one which gained increasing prominence in during the 1970s. Japan's reports on its national strategic ambitions were closely studied in Europe. Germany prioritised six areas in a programme on biology and technology launched in 1972: food and feed supplies, pollution reduction, pharmaceuticals, new routes to raw materials, chemicals and metals, and basic research on biotechnological processes, and Research Ministry support for the biotechnology programme more than doubled between 1974 and 1979 in the wake of the oil price shock. Britain, distracted by questions of what to do with a chemical and biological warfare laboratory, developed a coherent strategy with the Spinks report of 1979, seven years behind the equivalent German reference point, but with greater emphasis on biotechnology 3, recombinant DNA approaches. In the same year, the European Union, through its FAST[7] programme, established a three phase imaginary for Europe's socio-technical future in the same year: short term, the future of work and employment; within 10-15 years information and communications technologies might be expected to cause major change, as would the new biotechnology within 30 years (Bud, 1994, pp 141 - 160).

The broader social response to attempts to develop and commercialise biotechnology 3 products is a more complex story. At least in Europe, "red" (pharmaceutical and genetic testing) biotechnology was much more acceptable to the public than "green" (genetically modified crops or food) (Fiechter, 2000b; Bonfadelli et al. 2007; Peters and Sawicka, 2007). Bauer (2005) shows that over the 1990s red biotechnology enjoyed continued (if somewhat diminishing) public support in an analysis of 12 European countries. Green biotechnology lost public support during the same period. At the extreme:

> " ...the majority of people in Switzerland would not buy GM food even if it were (i) cheaper than conventional food (87%) ; (ii) contained less fat (82%); (iii) tasted better (70%); (iv) contained

[7] Forecasting and Assessment in Science and Technology

> fewer pesticides (57%) or were produced in an environmentally better way." (Bonfadelli, *opus cit* p. 118))

Because biotechnology was introducing experimental products (or variants on familiar products such as GM tomato paste) into mature markets, opposition to GM food crops could not only be expressed by trashing crops under field trials, but through consumer boycotts. In such markets as the UK, consumer resistance could be amplified by large-scale food suppliers like Northern Foods deciding not to stock GM foods.

Why did this red/green distinction take hold? Bauer finds no consistent pattern of press influence on public attitudes, although green biotechnology receives less favourable media treatment in a number of countries. Portinga and Pidgeon (2007), reviewing the UK GM food controversy, conclude that public acceptance is critical for the uptake of new technology, and that losing trust over the UK's BSE crisis may have led to a more general loss of public trust over the UK government's capacity to regulate a complex new technology such as GM food. (see also Grove White et al 1997; Jasanoff, 1996). However, this does not explain why UK attitudes too were less favourable to green biotechnology, which is no more complex than red.

American attitudes to GM foods offer some part of an explanation. Analysing findings of Polls under the Pew Initiative on Food and Biotechnology, 2001-2005, Fink and Rodemayer (2007) conclude:

> "Americans... are much more supportive of applications which they feel will be most beneficial to themselves, their family or society as a whole; they are less supportive of applications that, on the surface, appear to help only businesses or individual industries." (p.127)

Where the same societal benefit can be secured through a green rather than red route, this is preferred:

> "...making affordable drugs by the use of plants was listed as one of the most favourable reason for genetic modification, whilst making affordable drugs using animals was one of the least favourable reasons for genetic modification." (p. 149)

More generally, the spatial distribution of perceived risks and reward may influence European publics differential responses to red and green biotechnology. Genetically modified animals can be held as an encapsulated technology, separated from the ambient environment, and such separation extends, at least to some extent, to any human medical treatments derived from them. By contrast, despite attempts to specify minimum separation zones in the cultivation of GM crops, they are essentially non-encapsulated, open to the environment, and the extent of unintended genetic transfer and consequential effects on the food chain was much contested at the height of the European debate. As has been speculated (eg. Rayner, 2003) the relative greater rarity in Europe of wild environments untouched by urban or agricultural development may be one reason why sensitivity to further potential environmental damage from GM crops is greater than in the United States, with its huge wilderness reserves.

This discussion of the spatial and temporal distribution of risk and reward is broadened below in section three below, in relation to geoengineering and medicine.

The biotechnology case illustrates how a number of processes underlying stabilisation develop in wider historical and national settings. 'Biotechnology' might be seen to be an adaptive term which was to sets of technologies embodying claims of increasing control over nature: first applied retrospectively to technologies based on selection of natural processes, then to process technologies able to apply chemical processes to control and extend the range of biotechnological products at industrial scale, then through the epistemological shift provided by the recombinent DNA technology coming out of molecular biology, vastly greater control - biotechnology 3 - which leads directly into nanotechnology as one of the technological approached to the manipulation of the very small.

This progressive stabilisation provided continuity against change, most importantly in the shape of industry which was able to adapt to provide legitimisation and funding for change, most notably in the development of penicillin and its successor antibiotics, whose public acceptability may have been eased by their arrival during a world war. By the advent of biotechnology 3 in the 1970's the world was assimilating the oil price shock caused by the reduction of production by the OPEC countries, allied to a rise in environmental consciousness that suggested this as symptomatic of wider limits to growth. Because of these perceived challenges, and because the technical practices of biotechnology 3 were still immature, this phase of development is marked by national imaginaries and strategic reports designed to spur technological change along paths seen as aligned to countries interests and capacities, in the hope of appropriating its benefits for national competitiveness.

Biotechnology also provides an important insight into conditions for the last stage of stabilisation, public response. Lezaun points out that:

> "the stabilisation of the category of 'biotechnology' is to a large extent a regulatory process, and is driven, mostly in Europe but also internationally, by a movement of opposition that led to the legal definition of 'biotechnology' as a distinct form of biological modification - a process-based definition of the field, in Jasanoff's terms (Jasanoff 2005). This suggests that stabilisation can also be the result of opposition/resistance (not just of public consent), provided governments are willing to act and stabilise a fluid technological field for the purpose of regulating it. "[8]

The acceptability of 'red' compared with the resistance to 'green' technologies points up the importance of praxis - of the uses put to (in this case very similar) technological practices and the spatial, social and temporal distribution of the envisaged risks and benefits which are foreseen.

Nanotechnology

Like Geoengineering, nanotechnology comprises a large range of technical practices, focused on the control of scalar extremes - in this case the very small. Unlike geoengineering, the uses of nanotechnology cover a vast range of social and commercial products and processes. In theory that range is unlimited - nanotechnology has been described as the ultimate technology (Dinello, 2005), since in principle our whole environment and ourselves could be reshaped by it, with molecular precision. Extrapolations from this trope of ultimate control (sometimes running out

[8] Javier Lezaun, personal communication, November 2014.

of control) has lead to a large utopia and subtopia literature, both in futurist discourse (Drexler, 1986; Kurzweil 2005) and in science fiction (Atwood, 2003; McAuley, 1995).

Like biotechnology, practices which we would now classify under the heading of nanotechnology have a long history. Nanomaterials date back to Roman craft practice in the creation of dichroic glass, embodying colloidal gold and silver which allows for colour changes depending on whether the object is lit from within or without, a process first understood by Michael Faraday in 1857. Similarly the manufacture of certain kinds of swords in the Islamic world from the 13th to 18th centuries from a particular kind of ultra-high carbon steel containing carbon nanotubes and cementite nanowires gave strength, resilience and a hard edge. (NNI, 2014, Nanotechnology Timeline, quoting Reibold et al., 2006).

The modern history of nanotechnology usually is said to originate in Richard Feynman's lecture to the American Physical Society meeting of 1959 entitled *There's Plenty of Room at the Bottom* (Feynman, 1960), although the term nanotechnology wasn't coined until 1974[9]. The less often quoted subtitle of the address - *An Invitation to Enter a New Field of Physics* - explicitly frames the address as an exercise in enrolment of his fellow physicists. Feynman gives examples of strategic targets for the new field and offers two personal cash prizes as incentives: for a page of text at 1/125 scale, readable by an electron microscope, and for an electric motor in a 1/64th inch cube (won in 1960).

Similarly the author of what we can term the nanotechnology imaginary is usually seen to be K. Eric Drexler in his technical 1981 paper focused on the opportunities and risks brought by the development of molecular replicators and assemblers (Drexler, 1981) and in his popular book on the same theme (Drexler 1986). In a continuity with the use of imaginaries in biotechnology, Drexler saw himself as constructing a counter-narrative to the influential *Limits to Growth*, (Meadows, et al, 1972) which itself had borrowed from Malthus, and which had been focussed on the constraints in resources available to a world growing in population and ambitions for consumption. For Drexler, the nanotechnology imaginary was of a technology which would overcame resource constraints, rendering everything possible at very low cost: and he self-consciously organised

[9] by Norio Taniguchi (Taniguchi, 1974).

his academic life around developing the concept and spreading the word (Regis, 1995). By 1992 he had given evidence to a U.S. Senate Committee and the Office of Science and Technology Policy at the White House on the transformative potential of nanotechnology, which he calculated would be unleashed in 15 years.

The final stages of stabilisation of nanotechnology was based in the agency of Mihael Roco, who like Weaver did this from a funding role, in this case at the United States National Science Foundation (NSF). Roco sought to bring together a diverse array of technical practices focussed on the manipulation of the very small, and offered them a route map for development and funding. He ran the NSF's first programme on nanoscale science and engineering in 1991 and

a cross disciplinary programme - "Partnerships in Nanotechnology" - in 1997 -98. Roco writes;

> "However, only in 1998-2000 were the fragmented fields of nanoscale science and engineering brought together under a unified science-based definition and a ten year R&D vision for nanotechnology. These were laid out in the 1999 NSF workshop report *Nanotechnology Research Directions* (Roco et al. 1999) which was adopted in 2000 as an official document by the National Science and Technology Council. These were the defining steps towards establishing nanotechnology as a defining technology of the 21st century." (Roco, 2011)

Roco by this stage was moving at prodigious speed. He proposed the National Nanotechnology Initiative (NNI), at a meeting of the White House/Office of Science & Technology Policy in 1999. The NNI, founded in 2000, represented stabilisation on a very large scale - it brought together the nanotechnology initiatives of 20 US Federal departments and agencies "creating a framework for shared goals, priorities and strategies...with the help of the NNI, nanotechnology R&D is taking place in academic, government and industry laboratories across the United States." [add ref to Act] The budget of the NNI has risen from under $500 million in 2001 to over $1.5 billion for 2015. It supports a broad portfolio of nanoscale science, engineering and technology at 11 agencies, with another 9 agencies having nano related missions, or regulatory responsibility (NNI, 2014).

The potential power of nanotechnology led to issues of governance being prominent from early stages. *Engines of Creation* devotes three chapters to the unintended, unforeseen and intentionally malign dangers, to the means of countering them through "personal restraint, local action, selective delay, international agreement, unilateral strength and international collaboration" and through open, due process "science courts" to uncover the facts behind scientific controversies. (Drexler, 1986, pp 196 and 212).

The public participation role in nanotechnology governance is more mixed.

In Europe, the management of the European nanotechnology integrated programme launch under the sixth Framework Programme was determined to learn from what it saw as the public relations disaster of GM foods. It commissioned a report on the specific risks its programme faced (Healey & Glimell, 2004), specifically focussed on the roles that social sciences could play, and followed up with a major strategy report (European Commission, 2004).

In the United States, the 21st Century Nanotechnology Research and Development Act (2003, S.189, 108th Congress), enabling the establishment of the NNI, required the program:

> "to take specified steps to ensure that ethical, legal, environmental and other appropriate societal concerns during the development of nanotechnology"

and included a specific role for public participation. These arrangements were criticised as being too "downstream", related to a relatively unproblematised concept of success, and excluding social science analysis of the social dimensions shaping the programme's technologies and knowledge (Macnaghten et al., 2005). Although the two Centers for Nanotechnology in society set up in Arizona State University and University of California at Berkeley have widened the academic discussion of nanotechnology's social origins and impacts, there is little evidence of impact on the programme itself, which carries out a parallel but largely independent discussion of the need for social approval and for regulation in periodic reviews of achievements and prospects (Roco et al., 2011).

Nanotechnology in the United States constitutes a paradigmatic story of stabilisation. It started by two imaginaries from two distinguished and imaginative scientists, the first creating an epistemic focus of the manipulation of the very small, issuing a challenge to physicists to adopt this as their focus parallel to the challenge that had been issued in relation to molecular biology a generation before; and the second imagining the range of transformative applications which the promised power and precision of the technology might bring. Roco was the focal figure delivering legitimacy and initial funding from a funding agency base, and pulling together and aligning efforts across federal government departments and agencies in a multi-year initiative backed by legislation.

This allowed nanotechnologies to achieve impetus, albeit using it as a flag of epistemic and policy convenience under which were grouped a wide range of physical, chemical and biological processes working within a large range of scales within the very small. In its slow development, its lack of epistemic unity, and its pursuit of governance issues whilst not taking full account of issues of public consent, the field is similar to geoengineering. However it differs in two important respects. The first is that nanotechnology potentially contributes to a vast range of products and processes, including technologies relating to climate change, whilst geoengineering focuses on climate change alone. The second is that this potential range of products led to it being coopted nationally as an instrument of economic competitiveness, with national programmes including efforts Brazil, China, Sri Lanka, Canada, Iran, Russia, Thailand, Ireland and Venezuela (see for example Kishi & Bando, 2004). In such cases the responsibility for an national investment strategy[10] and for regulating the pathways to successful innovation both fall initially to national authorities (Jarvis & Richmond, 2011).

[10] In the case of Russia, through a state investment arm, Rusnano. See http://en.rusnano.com/about. Accessed 15 September 2014.

3. Technologies of the individual and the planet: medicine and geoengineering.

Before drawing some conclusions for geoengineering assessment and governance, it might be helpful to go back to Mol's analysis in trying to see how the point of about the spatial distribution of risk and reward, brought in at the end of the discussion of the biotechnology case, might usefully be developed further.

As pointed out in the introduction, stabilisation may not be a unitary concept. Mol (2003) has pointed to the multiple, nested, almost recursive nature of stabilisations in clinical settings:

> "there can be multiple stabilisations at play when it comes to 'doing disease'…In a single medical building there are many different artheroscleroses…these somehow 'hang together' through a kind of coordination between lab technicians, machines, doctors, nurses, patients and others."

In Mol's clinical example the glue for the 'meta-stabilisation' of these different technical practices is their existence as part of a wider task of delivering diagnosis and treatment. Indeed the component technologies - imaging, pharmacology, surgery, etc., - only gain meaning through being situated in this way, in their relation to praxis. In section 4 we explore whether geoengineering can usefully be thought of in these terms, as a meta-stabilisation of a range of technical practices.

However, there is another more obvious set of ways in which clinical decision-making and geoengineering are quite different. Clinical decision making as to diagnosis and treatment, although of course constrained by the medical resources on offer which themselves have a history, represents a very concentrated form of sociotechnical choice. Clinical decision-making:

> - is concentrated in its targets in that the risks and rewards affect a single individual;
>
> - is concentrated in that the only parties who need to make the key choices of what medical treatments to deploy are the patient - the sole stakeholder - and her or his medical advisor;

- it is relatively concentrated in the range of sociotechnical practices – micro stabilisations - that are mobilised in the course of such a treatment;

- the selected treatment often has to be temporally concentrated too if it is to be effective;

- the impacts of treatment are likewise intended to be concentrated on the patient (although in this case the effects can be wider: herd immunity, increased antibiotic resistance, or the environmental dispersion of endocrine disrupting hormones can all be positive or negative social side-effects of individual patient treatments)

- the criteria of medical success are by and large clear, and there is a powerful selection effect in the telling of the results post-hoc: the cured tell a good tale, and as we have learned from Goldacre [2008] big pharma buries not only individual patients, but also the results of unsuccessful clinical trials. Reversability is not (at least at present) an issue with the dead.

By contrast, choices regarding research or potential deployment in climate geoengineering represent a very diffuse range of options. Geoengineering presents:

- a very wide range of immature technologies, developing rapidly;

- these may aim at increasing the earth's albedo or at CO_2 capture;

- they may be high-tech or seek to enhance the planet's natural processes;

- they can be encapsulated or open to the environment;

- if open to the environment, they can be deployed on land or in the ocean, atmosphere or space;

- they are massive in scale: by definition they aim at planetary effects and thus involve decision makers across many jurisdictions invoking current laws and regulations or prescribing new ones;

- there are considerable uncertainties and differences as to when if ever they would be called upon and the appropriate end-point (the ideal temperature for the planet, unlike that for the individual patient, is a contested social construct);

- the risks and rewards but may be spread differentially, with huge groups of winners and losers (as of course is also the case with unmodified climate change). Further what constitutes success will be contested, not only across jurisdictions but between different interests within them;

- some technical options may not be reversible should unintended consequences dictate the need for this.

The parallels are with the distribution of risk and reward in red and green biotechnology. These make a significant difference to the governability, and the perceived acceptability, of the technologies concerned. More concentrated patterns of risk and reward, as can be seen in technologies of the individual which medicine exemplifies, make decision-making simpler. For the individual, the risks of morbidity or mortality will seem real and immediate enough to make a choice of medical options compelling. Since some medical treatment may seem essential, and because all medical choices involve some kind of trade-offs between the mature treatment and the experimental, between present and future medicine, patient choices also provide impetus to more medical innovation, and the processes that approve or ration new medicines, new prostheses or new procedures. Further, there is by and large a single and unambiguous set of criteria by which medical success or failure can be judged, relatively uniform across all cultures, although culturally preferred routes to successful outcomes vary.

Social choice, and even the individual's role in social choice, may seem considerably more complex where the trade off might seem to be between the local environment and a new agricultural product. They might seem impossibly complex when global or planetary-scale issues are involved, and different values and interests come into play.

Some of the potential interplay of national imaginaries of development and the opportunities and risks of geoengineering can already be seen. In China, there seems to be a resistance to deploying SRM through stratospheric aerosols, yet the country has a strong history of weather modification which might suggest that efforts at climate control might be in acceptable in some circumstances. If the country decided to go down that track it already has the logistical and institutional capacity to do so; similarly China's rapidly developing space capacities would put it in a strong position to deploy space mirrors to reflect sunlight, which seems to be an approach that is being entertained. [11] In the United States, SRM narratives are couched in value for money terms, another cultural trope, despite huge uncertainties in costing (MacKerron, 2014).

Perhaps Germany, in line with national narratives, will re-discover the need for forest cover, and biochar. SRM narratives in the US are couched in value for money terms, another US cultural trope, as well as appearing to at least postpone the pain for the carbon energy industries.

4. Geoengineering, stabilisation and governance: what can we learn?

A changing context for science and technology governance

Our case studies span some eighty years. This period has seen three long-term trends in the contexts for science and technology policy. The first has been a strong and continuing secular trend in national appropriation of science and technology assets for strategic and economic purposes, which has become a global phenomenon. The second has been a long period after world war two with a rising emphasis on problem solving through institutions of global political and economic governance and a degree of Western consensus about economic orthodoxies which the Bretton Woods institutions would promulgate; a consensus which started to decline at the moment of apparent western triumph, the end of the cold war, when the reality of diversity in global interests and values emerged from behind the meta-narratives of east and west. The third, within Western societies, and particularly Western Europe, has been an increasing interest in defining, assessing, and securing, public acceptance of socio-technical change. The interplay between these three dynamics shape the space for science policy.

[11] this view of possible developments in China suggested by Steve Rayner, private communication.

Lessons from the case studies

The case studies are variants on a core story about the factors for success in stabilisation of a new technology: an important role for individual or institutional agents promoting the field, and providing not only a coherent epistemological and ontological narrative about its possibilities, but also funds to support early work. These actors used imaginaries in support of their activity: these always involved promises as to the power of the technology to meet a range of human needs, but increasingly, as we moved from molecular biology through the new biotechnology to nanotechnologies, invoked the need to capture that promise in the service of national economic competitiveness, and involved national funding bodies or the preparation of ad hoc strategic reports. This is particularly evident in the biotechnology case, but the 60 year history of our cases taken together show a progressive nationalisation of science. A strong epistemological thread of control over nature runs through all three of our examples, with each having their strong individual epistemological focus. In biotechnology the focus of modification of natural organisms itself progresses from fermentation products through enzyme technology to recombinant DNA technology: a progression of control within the wider control narrative linking the cases.

Re-framing the issue

By contrast with these cases, geoengineering governance confronts us with a wide range of immature and contingent technologies appealing to a wide variety of (sometimes dual-use) policy niches, over a variety of scales and timescales.

In its diversity, geoengineering doesn't seem to show the same features of stabilisation in the terms we have thought about these other emergent technologies. It employs a wide range of technological practices, but with no epistemological focus to unite them. In relation to the breadth of the technologies proposed, there have been rather limited efforts to counter the immaturity of the field by driving geoengineering research forward.

What might be seen as geoengineering's core document, the report *Geoengineering the Climate* (Royal Society, 2009), proposed international, European and UK programmes of research which have only been partially fulfilled in terms of the scope work or the scale of funding, but as a body it was in no position to follow up its own recommendations with financial commitments. There has been since no international (in the sense of trans-continental) research. Europe has funded an assessment project, EuTRACE, due to report in 2014, as are three UK funded projects: to test an approach to SRM, to provide a wider socio-technical assessment of geoengineering approaches, and to look at issues of geoengineering governance. Even this UK funding has fallen short of the £10m per year which the Royal Society proposed. There has been comparatively little from the public sector in the United States (the NSF was reported to have spent $100m on geoengineering research in the 2009-10, against requests of over $2bn, although NSF sources suggest that their funding commitment on a strict definition of geoengineering has so far totalled closer to $2m). [12] [13]The Bill Gates financed Fund for Innovative Climate and Energy Research (Ficer), which has committed $5m, has been very limited in its spread of largesse, nearly half of its research funds going to the two scientists who run it. [14]

The prescribed scope of the first stage of the German Research Foundation (DFG) Priority Programme[15], launched in May 2013, illustrates the reluctance of government funding bodies to get directly involved in the direct development of geoengineering technologies. The programme objectives are:

- Investigation of the climatic, ecological and social risks and potential effectiveness of different Climate Engineering methods
- Evaluation of the scientific and public perception of Climate Engineering

---

[12] *The Guardian*, 6 February 2012
[13] a search of the NSF database on 25 August 2014 suggests that it awarded 6 grants on geoengineering between 2008 and 2014 for a total of $1,964,123
[14] See http://dge.stanford.edu/labs/caleiralab/FICER.html. Accessed 25 August 2014
[15] Climate Engineering? Risks, Challenges, Opportunities? DFG Priority Programme (SPP) 1689. See http://www.spp-climate-engineering.de/focus-program.html. Accessed 25 August 2014. A second stage of the DFG programme is yet to be defined.

> Assessment – not development! [original emphasis] – of Climate Engineering, including scientific, social, political, legal and ethical aspects

So we can see that in comparison with the theory and our other empirical cases, geoengineering currently lacks epistemological focus, lacks legitimacy, despite the IPCC having held an expert meeting on it and having discussed it briefly under AR5, and lacks funding at any significant scale. Does this apparent lack of progress in the stabilisation of geoengineering matter? I rather think not. It may be that thinking about geoengineering in these terms was to adopt the wrong target, and that as Heyward (2013) and others are right in their analysis in maintaining that geoengineering has no conceptual unity in technological terms alone: the identity of GE comes as a set of sociotechnical options designed to contribute to climate modification on a global scale.

Macnaghten & Szersynski (2013) sees this global scale of geoengineering as the core of its exceptionalism as a technology, but one that they reject outright. In particular they see SRM as a hubristic "political project of planetary control" which can only be governed by a central authority - this in their view makes it intrinsically undemocratic, and therefore unacceptable.

I follow Heyward and Rayner (2013) in thinking they are wrong in this. Rather it can be argued that this politico-technical nature of GE does not support an argument in favour of GE exceptionalism, but rather helps us to see the parallels between GE, mitigation and adaptation, and the analytical and policy benefits of treating the challenges of all these approaches to climate change management in symmetrical ways. Bellamy et al (2013), using multi-criteria mapping, have shown robust public attitudes favouring mitigation when GE and mitigation options are presented as alternatives; Scheer & Renn (2014) in a recent review of public engagement over GE, have also pointed up the danger of narrow framing: when judged in isolation, at least one third favour GE, preferring CDR over SRM; when judged against mitigation, GE options lose support. Framing the issue as a wider problem of climate policy, rather than restricting it to GE, might be expected to lead to radically different answers.

Thus I would argue that whilst GE subtechnologies require separate technical assessment for (cost- effectiveness, opportunity and risk and uncertainties); when it comes to public debate and the development of climate change policy, and in thinking through governance options, it may be useful to try to frame all geoengineering, mitigation and adaptation choices as sociotechnical options, to considered in parallel and in combination.

We can draw further on Mol at this point. If we shift focus from geoengineering as a unitary enterprise we can see see geoengineering's various sub-technologies as highly dynamic recursive systems within the larger system of climate change management. This shift of approach carries the danger of in some sense 'normalising' geoengineering, but it also allows for direct hard headed comparisons of routes to a variety of environmental, food production and energy goals centred on (but not confined to) climate change objectives. Such a re-framing would bring most benefits, analytically - not least by encouraging further attention being given to the socio-technical barriers to mitigation and adaptation, and by giving attention, for example, to the importance of the apparently rapid developments in technologies for energy production and storage. [16] An end to the exceptionalism of treatment of geoengineering - a framing employed both by some advocates and critics - would allow geoengineering's diverse component approaches to find their sociotechnical place alongside others.

Such a development would also help the framing of a policy debate which fully engages the public. That debate is important, since it is not just geoengineering that is lacking a social licence to operate: it would seem to be true at least to some extent of all approaches to climate policy.

Forms of public debate and of governance

Much discussion to date has concentrated on the democratic deficit in governing climate change and geoengineering. Branson (2014), focussing on ocean iron fertilisation, has recently argued against separate regulatory standards for GE research: against the CBD limited consent to

[16] Gardiner (2011) has argued that the attention given to geoengineering has served to distract from the attention that might be given to Manhattan project scale alternative energy projects.

GE research, and the London Convention/London Protocol assessment framework, maintaining that these have not been strong enough to prevent the unilateral action of Russ George's 2012 Haida Salmon ocean fertilisation experiment, yet have been strong enough "to slow the pace of legitimate research and distract from a serious discussion about the risks and benefits of...geoengineering methods." He has suggested the UNFCCC as the appropriate home of a new geoengineering research protocol, noting that the UNFCCC could also prohibit carbon credits being earned in such experimental settings. Others such as Ralph Bodle, also favour a single global government agency, in this case by extending the writ of the Convention on Biological Diversity (CBD) [Bodle, Oberthür et al. 2014). Focusing on stratospheric aerosol injection, Mike Hulme (2014) favours an outright ban on this particular geoengineering option, whilst David Keith has come close to arguing that scientific self-regulation and responsibility should lead governance regulation, at least at a small scale of experiment (Keith, 2013). All these positions under-express the potential role of public engagement in setting objectives and regulatory criteria for climate change.

The objectives, styles and outcomes of public engagement in technology governance have been much debated over the last two decades. Processes and uses of engagement have reflected, often implicitly, wider governance styles, ranging from discretionary to agonistic (Hagendijk & Irwin, 2006), and occasionally have been seen as the means of legitimation of pre-determined outcomes.

One does not have to accept Macnaghten & Szersynski's essentialist argument that geoengineering is intrinsically undemocratic because of the scale of its ambitions isn't justifiable, in order to believe that public engagement on geoengineering and other approaches to climate management are underdeveloped. This may be related to the scale and nature of the sociopolitical forums in which climate change is diagnosed and discussed: with the scale and style of problem diagnosis and treatment and the imperatives to seek closure, and thus to embrace "unitary and prescriptive" policy advice. (Stirling 2005). Climate change analysis can be seen as largely the preserve of an intergovernmental technocratic project, whose prescriptions are subject to discussions between states on global norms, with action at the national level. The space left to debate can seem reactive to predetermined options rather than constitutive of the plural sources of policy advice which Stirling advocates for their ability to recognise contingencies, allow for contestability and enhance the accountability of the positions arrived at. This more nuanced, plural, bottom up conception of engagement has been developed further by Visvanathan (2005) in his proposal for cognitive justice which

> "... recognises the plurality of knowledge systems. It also recognises the relation between knowledge and livelihood and lifestyle" (p.92)

What seems to be needed is an approach to participatory governance of climate change a more progressive, decentralised, cumulative, step by step approach, building on protocols and principles (Rayner and Caine, 2014). Organising inclusive debate in this context - inclusive in terms of countries and interests - is a major socio-technical challenge, which social scientists should seek to mediate, but with due respect for local political processes. Debate needs to look at the range of solutions proposed for climate change, taking account of the stock of greenhouse gasses as well as the flows of new emissions, and taking related issues like energy and water policy, and agricultural production, on board, building on the experience of such international initiatives as the Solar Radiation Management Governance Initiative (SRMGI)[17]. It will have central objectives, protocols, standards and databases, but will also be in local ownership, allowing it to be responsive to local political environments, and will produce local and regional unilateral, bilateral and multilateral solutions as well as build towards wider frameworks of governance of experiment and action, all in line with the evolving principles and thus with rigorous and standards of evaluation built in. Not least of the challenges of achieving cognitive justice through such an approach will be as to reconcile the plurality of future visions within a country, as well as exploring how these might be used to constitute a wider global governance order, building where possible on existing mechanisms, laws and treaties.

[17] http://www.srmgi.org

Approaches to the assessment of geoengineering that are, as Visvanathan suggests, "sensitive to the relation between knowledge and livelihood and lifestyle" are likely to explore the virtues of co-benefits - of looking for approaches to the management of climate that can also help address pressure on supplies of food, energy and water.

Discourse in one prominent on-line discussion group[18] has recently included general criticism of the perceived dominant role of social scientists in discussions of geoengineering governance, and a criticism from the group's moderator that a paper on the dangers of lock-in and path dependence in geoengineering technologies (Cairns, 2014) itself represented an unwelcome degree of path dependence on social science perspectives. The message was that geoengineering research should be rebalanced in terms of developing technical capacity, rather than wondering what might be done with it when we had it. What is proposed here - a gradualist, bottom-up and socially inclusive approach, seeing geoengineering in relation to the wider issue of climate change governance and other pressures on natural resources, is in sharp distinction to the discussion group's technology-led approach. This approach might be difficult to develop, but it would have the short-term benefit in raising the bar against "climate emergency" and "tipping point" framings which can seem to be the tools of special interests, and in the long term would have a chance of delivering longer-term and more sustainable approaches enjoying wider public assent, and as well as important other benefits besides climate change.

REFERENCES

Abir-Am, Pnina (1982) "The Discourse of Physical Power and Biological Knowledge in the 1930s: A Reappraisal of the Rockefeller Foundation's 'Policy' in Molecular Biology. Social Studies of Science, 12, 3, pp 341-382

Atwood, Margaret (2003) *Oryx and Crake*. New York: Doubleday

[18] https://groups.google.com/forum/#!forum/geoengineering

Bauer, Martin W (2005) "Distinguishing *Red* and *Green* Biotechnology: Cultivation Effects of the Elite Press." *Int J Public Opin Res* (Spring 2005), 17, 1, pp 63-89.

Bauer, Susanne and Wahlberg, Ayo (2009) "Introduction: categories of life" in Bauer, Susanne and Wahlberg, Ayo, eds (2009) *Contested Categories: life sciences in society.* Ashgate: Farnham, UK and Burlington, VT, USA.

Bijker, Wiebe E, and John Law, eds (1992) *Shaping Technology/Building Society: Studies in Sociotechnical Change.* Cambridge, Mass. and London, England: The MIT Press

Bodle, Ralph, Sebastian Oberthür et al. (2014) *Options and Proposals for the International Governance of Geoengineering.* Berlin: Ecologic Institute on behalf of the Federal Environmental Agency (Germany) - Report No. (UBA-FB) 001886/E

H.Bonfadelli, U Dahinden, and M.Leonarz (2007) "Mass Media and Public Perceptions of Red and Green Biotechnology: a Case Study from Switzerland" in Brossard et al (eds) pp 97-125.

Bowker, Geoffrey C. "What's in a Patent?" (1992) in Bijker and Law (eds) (1992) pp. 53-74

Bowker, Geoffrey C., and Susan Leigh Star (1999) *Sorting Things Out: Classification and Its Consequences.* Cambridge, Mass. and London, England: The MIT Press

Brossard, D., James Shanahan and T. Clint Nesbitt (eds) (2007) *The Media, the Public and Agricultural Biotechnology*. Wallingford, Oxon, CAB International.

Bud, Robert. (1994) *Uses of Life: A history of biotechnology*. Cambridge: Cambridge University Press.

Cairns, Rose (2013). *Geoengineering: issues of path-dependence and socio-technical lock-in.* Background briefing for the workshop of the same name organised under the Climate Geoengineering Governance (CGG) project, UCL, 25 October 2013.

Callon, Michel, John Law and Arie Rip, eds (1986) *Mapping the dynamics of science and technology: sociology of science in the real world.* Basingstoke: Macmillan

Collingridge, David (1980). *The Social Control of Technology*. London: Frances Pinter

Cooper, G., and S.Woolgar, (1994) "Software quality as community performance" in R.Mansell (ed) *The Management of Information and Communication Technologies: emerging patterns of control* (London: Aslib, 1994) 54-68

Demain, Arnold L., and Aiqi Fang (2000) "The Natural Functions of Secondary Metabolites" in A. Fiechter (2000a) *History of Modern Biotechnology 1* (Berlin, Heidelberg, New York: Springer) p.4

Dinello, Daniel (2005) *Technophobia: Science Fiction Visions of Posthuman Technology.* Austin, Texas: University of Texas Press

Drexler, K. Eric (1981) "Molecular Engineering: An Approach to the Development of General Capabilities for Molecular Manipulation". *Proceedings of the National Academy of Sciences,* 78, 5275-78 .

Drexler, K. Eric (1986) *Engines of Creation: The Coming Era of Nanotechnology*.
New York and Toronto: Random House (Anchor Books)

European Commission (2004) Towards a European Strategy for Nanotechnology.
htpp://ec.europa/eu/research/industrial_technologies/pdf/nanotechnologies_communication_en.pdf

Feynman, Richard P (1960) "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics." Originally published in *Caltech Engineering and Science,* 23:5, 22-36. Available on the web at: http://www.zyvex.com/nanotech/feynman.html

Fiechter, A (2000b) "Biotechnology in Switzerland and a Glance at Germany" in A. Fiechter (2000a) *History of Modern Biotechnology 1* (Berlin, Heidelberg, New York: Springer) p.180

Gardiner, S (2011) *A perfect moral storm: the ethical tragedy of climate change*. E-book - ISBN 0199897107. Oxford and New York: Oxford University Press.

Goldacre, Ben (2008) *Bad Science*. London: Fourth Estate.

Grove White, R.,, Macnaghten, Mayer S and Wynne B (1997) *Uncertain World: Genetically Modified Organisms, Food and Public Opinion in Britain.* Lancaster: University of Lancaster Centre for the Study of Environmental Change

Hagendijk, Rob and Alan Irwin (2006) "Public Deliberation and Governance: Engaging with Science and Technology in Contemporary Europe". *Minerva*, 44, 167-184.

Healey, Peter & Hans Glimell (eds. - 2004) Report on the workshop *The Social and Economic Impact of Research on Nanotechnologies and Nanosciences.* Brussels: European Commission, Research Directorate-General, Directorate G – Industrial Technologies, Nanosciences and Nanotechnologies, May 2004

Heyward, Clare (2013) "Situating and Abandoning Geoengineering: A Typology of Five Responses to Dangerous Climate Change." *Political Science & Politics*, 46, 1, pp 23-27.

Heyward, Clare and Steve Rayner (2013) "A Curious Asymmetry: Social science Expertise and Geoengineering." Climate Geoengineering Governance Working Paper no. 7, November 2013.

Hulme, Mike (2014) *Can Science Fix Climate Change? A Case Against Climate Engineering.* Cambridge: Polity Press

Jarvis, S.L., Richmond, N., (2011)"Regulation and Governance of Nanotechnology in China: Regulatory Challenges and Effectiveness" *European Journal of Law and Technology,* Vol. 2, No.3, 2011

Jasanoff, Sheila (1997) "Civilization and madness: the great BSE scare of 1996". *Public Understanding of Science*, 6 (3), 221-232.

Jasanoff, Sheila (2005) "Let them eat cake: GM foods and the democratic imagination" in Leach, M., I. Scoones and B. Wynne (eds), pp 183-199

Jasanoff, Sheila (2005) *Designs on Nature: Science and Democracy in Europe and the United States.* Princeton, New Jersey: Princeton University Press

Jasanoff, Sheila (2007) "Technologies of Humility". *Nature*, 450 (7166), p. 33

Jasanoff, Sheila and Kim, Sang-Hyun (2009) "Containing the Atom: Sociotechnical Imaginaries and Nuclear Power in the United States and South Korea", *Minerva*, 47, 119-146 (DOI 10.1007/s11024-009-9124-4)

Keith, David (2013) *A Case for Climate Engineering*. Cambridge, Mass., and London, England: Boston Review Books, The MIT Press

Kishi, Teruo and Yoshio Bando (2004) "Status and trends of nanotechnology in Japan" *Nature Materials*, 3, 129-131.

Kohler, Robert E (1976) "The Management of Science: the Experience of Warren Weaver and the Rockefeller Program in Molecular Biology" *Minerva*, 14, 279-306

Kurzweil, Ray (2005) *The Singularity is Near: When Humans Transcend Biology.* London: Duckworth

Latour, B (2005) *Reassembling the Social: An Introduction to Actor-Network Theory.* Oxford and New York: Oxford University Press

Law, John (1986) "The heterogeneity of texts" in Callon, Law and Rip, eds, pp 67-83

Law, John and Michel Callon (1992) "The Life and Death of an Aircraft: A Network Analysis of Technical Change" in Bijker and Law (eds) (1992) pp 21-52.

Law, John and Wiebe E. Bijker (1992) "Postscript: Technology, Stability and Social Theory" in Bijker and Law (eds) (1992) pp 290-308.

Leach, M., Ian Scoones and Brian Wynne (eds, 2005) *Science and Citizens*. London: Zed Books

McAuley, Paul (1995) *Fairyland*. New York: Avon Books

MacKerron, Gordon (2014) Costs and economics of geoengineering. Oxford: CGG Working paper 13. Available at: http://geoengineering-governance-research.org/cgg-working-papers.php

Macnaghten, P., Matthew Kearnes and Brian Wynne (2005) "Nanotechnology, Governance and Public Deliberation: What Role for the Social Sciences?" *Science Communication*, 27, 2, pp 1-24.

Macnaghten, P., and B. Szerszynski (2013) "Living the Global Social Experiment: An analysis of public discourse on solar radiation management and its implications for governance". *Global Environmental Change*, published online by Elsevier 21 January 2013. http://dx.doi.org/10.1016/j.gloenvcha.2012.12.008

Meadows, Donella H et al. (1972) *The limits to growth : a report for the Club of Rome's project on the predicament of mankind.* London : Earth Island

Mol, Annemarie (2003) *The Body Multiple: Ontology in Medical Practice.* Durham, N.C. and London: Duke University Press

Morange, Michel (1998) *History of Molecular Biology.* Harvard, Mass.: Harvard University Press

Mullins, N.C. (1972) "The Development of a Scientific Specialty: The Phage Group and the Origins of Molecular Biology", *Minerva*, 10, 51-82.

NNI (2014) - National Nanotechnology Initiative (United States) website - http://www.nano.gov. Accessed on 5 April 2014.

Peters, H.P. and M. Sawicka (2007) "German Reactions to Genetic Engineering in Food Production" in Brossard et al (eds), pp 57-96

Portinga, W., and N.Pidgeon (2007) "Public Perceptions of Agricultural Biotechnology in the UK: the Case of Genetically Modified Food" in D. Brossard et al (eds) *The Media, the Public and Agricultural Biotechnology*, Wallingford, Oxon, CAB International, pp 21-56

Ratner, Mark and Daniel Ratner (2003) *Nanotechnology: a Gentle Introduction to the Next Big Idea.* Upper Saddle River, New Jersey: Prentice Hall PTR

Rayner, S., (2003) "Why can't we agree?" *Newsweek*, 15 September 2003.

Rayner S., Heyward C., Kruger, T., Pidgeon, N., and Redgwell, C. (2013) "The Oxford Principles. " *Climatic Change*, 121, 3, 499-512.

Rayner S., and M. Caine (eds - 2014). *The Hartwell Approach to Climate Policy*. London: Routledge - Earthscan Science and Society series.

Regis, Ed (1995) *Nano: The Emerging Science of Nanotechnology*. Boston, New York, Toronto, London: Back Bay Books, Little, Brown and Company

Reibold, M, P.Paufler, A.A Levin, W. Kochmann, N. Pätzke and D.C.Mayer (2006) "Materials: Carbon Nanotubes in an ancient Damascus sabre. " *Nature,* 444, p 286.

Rip, Arie (1986) "Mobilising resources through texts" in Callon, Law and Rip, eds, pp 84-99

Roco, M, C Mirkin, M Hersam (2011) *Nanotechnology research directions for societal needs in 2020: retrospective and outlook*. New York: Springer

Royal Society (2009) *Geoengineering the Climate: Science, Governance and Uncertainty*. London: Royal Society - Policy document 10/09

Stirling, A (2005) "Opening up or closing down? Analysis, participation and power in the social appraisal of technology" in Leach, M., I. Scoones and B. Wynne (eds), pp 218-231

Taniguchi, N (1974) "On the Basic Concept of 'Nano-Technology'," *Proc. Intl. Conf. Prod. Eng. Tokyo, Part II,* Japan Society of Precision Engineering.

Visvanathan, Shiv (2005) "Knowledge, justice and democracy" in Leach, M., I. Scoones and B. Wynne (eds), pp 83-94

Walker, W. (2000) “Entrapment in large technology systems: institutional commitment and power relations.” *Research Policy*, 29, 833-846.

Weaver, W. (1970) *Scene of Change: A Lifetime in American Science .* New York: Charles Scribner’s Sons. pp 59-60