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Advanced Review

Climate geoengineering: issues of path-dependence and socio-technical lock-in

Rose C. Cairns*

As academic and policy interest in climate geoengineering grows, the potential irreversibility of technological developments in this domain has been raised as a pressing concern. The literature on socio-technical lock-in and path dependence is illuminating in helping to situate current concerns about climate geoengineering and irreversibility in the context of academic understandings of historical socio-technical development and persistence. This literature provides a wealth of material illustrating the pervasiveness of positive feedbacks of various types (from the discursive to the material) leading to complex socio-technical entanglements which may resist change and become inflexible even in the light of evidence of negative impacts. With regard to climate geoengineering, there are concerns that geoengineering technologies might contribute so-called 'carbon lock-in', or become irreversibly 'locked-in' themselves. In particular, the scale of infrastructures that geoengineering interventions would require, and the issue of the so-called 'termination effect' have been discussed in these terms. Despite the emergent and somewhat ill-defined nature of the field, some authors also suggest that the extant framings of geoengineering in academic and policy literatures may already demonstrate features recognizable as forms of cognitive lock-in, likely to have profound implications for future developments in this area. While the concepts of path-dependence and lock-in are the subject of ongoing academic critique, by drawing analytical attention to these pervasive processes of positive feedback and entanglement, this literature is highly relevant to current debates around geoengineering. © 2014 John Wiley & Sons, Ltd.

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INTRODUCTION

In recent years there has been growing academic[1] and policy interest in climate geoengineering—the large scale, intentional manipulation of the earth's climate system in order to attempt to counteract the effects of anthropogenic climate change. Alongside a number of other important policy issues, concerns have been raised over the potential for geoengineering technologies to shore up current dependence on fossil fuels (so-called 'carbon lock-in'[2]), or become irreversibly entrenched or 'locked-in' themselves,[3–5] becoming resistant to change even if negative impacts were later discovered. In particular, the scale of infrastructures that geoengineering interventions would require, and the issue of the so-called 'termination effect'[6] (whereby the termination of a programme of stratospheric aerosol injection (SAI) would result in rapid heating of the planet) have been discussed in these terms. Dynamics of 'lock-in' have been raised even in relation to the more purely discursive aspects of these challenges, where (despite the emergent and somewhat ill-defined nature of the field), it has been suggested that the extant framings of geoengineering in academic and policy literatures may already demonstrate features recognizable as forms of cognitive

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lock-in, likely to have profound implications for future developments in this area.[7]

The wide ranging literature on path-dependence and socio-technical lock-in is illuminating in helping to situate current anxieties about irreversibility and climate geoengineering in the context of academic understandings of historical socio-technical developments and persistence. This review will provide a brief overview of the literature on lock-in and path-dependence, highlighting a number of ongoing theoretical debates and methodological challenges associated with assessment of these processes; it will then explore the way in which these concepts have been invoked in the existing literature on climate geoengineering. The article concludes with a critical reflection on the potential of these conceptual frameworks to contribute to a better understanding of different forms of irreversibility within the emerging discourses and practices of climate geoengineering.

Theorizing Socio-Technical Development and Persistence

Path-dependence and lock-in[8–10] are concepts with roots in evolutionary economics and the history of technology, that are now widely used across a range of social and political sciences[11] to describe and theorize the ways in which technologies, or more broadly socio-technical systems,[12] develop and may become resistant to change. Path-dependence refers, at the most basic level, to the fact that 'history matters' in understanding socio-technical development. The original conceptualization of path-dependence in the economics literature emphasized that path-dependent processes emerge initially from contingent (chance, random) circumstances that confer an initial advantage on a particular technology, followed by self-reinforcing processes or positive feedback, such as cumulative cost reductions and learning effects linked to increasing returns to adoption.[8,13] Within path-dependent processes, the sequencing of events is held to be particularly important, with earlier events mattering more than those occurring later. As Pierson puts it:

> Specific patterns of timing and sequence matter; starting from similar conditions, a wide range of social outcomes may be possible; large consequences may result from relatively "small" or contingent events; particular courses of action, once introduced, can be virtually impossible to reverse.[11]

Lock-in is a way of conceptualizing the outcomes of path-dependent processes, and describes how particular technologies—through their co-evolution with social, institutional, cultural, and political systems—may become resistant to change, 'closing down' or constraining possibilities for the development of alternative (possibly superior or more socially/environmentally desirable) socio-technical configurations. The potentially negative impacts of technological lock-in—also sometimes referred to as entrapment,[14] or entrenchment[9]—include a host of environmental and social problems such as climate change, ecological degradation, resource depletion, pollution, health and social problems. These impacts which in general are only 'belatedly discovered after the system' is well established.[15] A classic example of a 'locked-in' socio-technical regime is the transport system based around the use of the private motor car.[16] As Shackley and Green explain:

> the private car has had a profound influence on the structure of the city and its surrounding region, but it is no readily reversible effect as the mass availability of the car becomes part and parcel of everyday lifestyles and patterns of social and economic activity.[17]

Other paradigmatic examples of instances of socio-technical lock-in accompanied by undesirable impacts that are difficult to ameliorate, can be found in the fossil fuel energy generation and distribution system,[2] nuclear industry,[14,18] systems of industrial agriculture,[19] and urban infrastructures,[20] such as sewage systems.[21]

In addition to the aforementioned processes such as cumulative cost reductions, identified in the original economics literature on path-dependence and lock-in, a growing body of work has identified a number of additional drivers and processes linked to path-dependent outcomes. These include cognitive or epistemic processes, such as the effects of technological paradigms,[22,23] the importance of path-dependent processes in institutions,[24–26] which can range from legal systems[27] to less rigidly defined culturally accepted 'ways of doing things', or everyday practices;[21] and notions such as the 'technological regime', defined as the 'the whole complex of scientific knowledges, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructures that make up the totality of a technology'.[28]

Given that lock-in of particular socio-technical configurations can act to constrain future choices in profound ways, understanding path-dependent processes and lock-in of different types has important implications for democracy and social justice. For example, it has been observed that the proximate social forces shaping early configurations of artifacts and technologies (as well as routines, practices

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and paradigmatic ways of thinking) 'typically reflect the "needs" preferences, normativities and interests of rather restricted social groups',[29] with the result being that the diversity and direction of technological change in areas as diverse as agriculture, pharmaceuticals, energy, the military, and communication, has historically been constrained by powerful socioeconomic and institutional-political pressures.

Maintenance of the social control of technology and the prevention or amelioration of negative impacts of technological development are the normative concerns of the broad field of technology assessment (TA). Much work in this area builds on the work of Collingridge,[9] who famously described the question of societal control over technological development in terms of a 'dilemma' whereby in the early stages of a technology's development while the technology is still relatively easy to control, the impacts of technologies are largely unpredictable/unknowable; but by the time impacts are known, control is often impossible or very difficult. Collingridge argued that maintenance of flexibility in the face of unpredictability was a means of mitigating the negative impacts associated with lock-in, and that 'the essence of controlling a technology [was] not in forecasting its social consequences, but in retaining the ability to change a technology, even when it is fully developed and diffused'.[9]

It has been observed that lock-in of a particular technology is likely to imply 'lock-out' of others,[30] and hence the erosion of diversity,[29] which may happen by chance, or through the deliberate actions of advocates for particular technologies.[14] Hence, it has been suggested that one way in which flexibility can be sustained (and damaging lock-in avoided) is through the maintenance of diversity.[14,15,29] For example, Walker's case study of the nuclear re-processing industry provides evidence of the negative effects of a loss of diversity leading to entrapment, and for the need to 'ensure that alternatives survive and develop, that switching costs are not held unnaturally high, and that extrication is given due and timely attention'.[14]

Socio-Technical Lock-In and Climate Geoengineering

The term 'lock-in' features relatively prominently in the academic and policy discourse around climate geoengineering to date. However, reflecting its diverse usage in the broader academic literature, exactly what is meant by the term is not necessarily consistent, and it has been invoked to refer to a number of different processes or give voice to a number of different kinds of concerns. Within the academic and policy literature on geoengineering, two broad levels of analysis can be discerned: a focus on particular technologies or classes of technology and the potential mechanisms and consequences of lock-in that might result from their development and deployment; and a focus on the broader context of existing fossil fuel dependence or so-called 'carbon lock-in', and the ways in which particular technologies might disrupt or reinforce this. In the former category, the issue of socio-technical lock-in has been cited as a policy concern in a number of high-profile reports on geoengineering, including the Royal Society Report,[4] the UK House of Commons report on the Regulation of Geoengineering,[31] and the 2012 report by the Convention on Biological Diversity.[3] The need for assessment of the risk of lock-in was also a component of one of the so-called 'Oxford Principles' for the governance of geoengineering.[5] Some authors[5] distinguish between technical and social lock-in: technical lock-in being used to refer to the kinds of commitments that would accompany particular technological approaches such as SAI due to the existence of the so-called 'termination effect'. The term is used to refer to the fact that if a programme of Stratospheric Aerosol Injection were implemented but then discontinued, there would be a rapid spike in global temperature that would likely be more damaging than the more gradual temperature increases that would have taken place in the absence of such an intervention,[6] hence societies would be 'locked-in' to continuing the activity. Social lock-in, in this case, is used to refer to the ways in which many of the proposed technologies [e.g., direct air capture (DAC)], would be dependent on the existence of a highly capital-intensive physical infrastructure, the large sunk costs in which would create vested interests in keeping facilities operational, and hence would lead to various types of inertia and lock-in.[32]

On the other hand, the term lock-in has also been used to highlight the perceived risk of forms of regulatory lock-in to particular commitments (e.g., a total ban on testing), that might be regretted or have unintended consequences in limiting possible responses to emergency climate change.[33]

Other work has drawn attention to the importance of framing effects and what could be called 'cognitive lock-in'. For example, Bellamy et al. carried out a review of appraisals of geoengineering methods. They highlight the ways in which instrumental framing effects impact on the outcome of appraisals in important ways, acting to promote apparently preferable decision options given those framing effects that are privileged. In particular they illustrate the impact on outcomes of the choice of contextual problem frame within which appraisal of geoengineering takes place (e.g., the idea of climate emergency or the failure

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of mitigation), the choice of appraisal methods applied (e.g., the use of expert-analytic methods such as computer modeling, economic assessment and expert opinions), and the particular options appraised (e.g., the choice to focus on a limited number of geoengineering options, or to compare geoengineering options in contextual isolation rather than with the wider portfolio of responses to climate change). They draw on the concept of lock-in to argue that:

> As an upstream suite of technology proposals, [geoengineering proposals] are particularly sensitive to ... instrumental framing effects and could easily be quickly and prematurely closed down, locking us in to certain technological trajectories but not others ... potentially unsung divergent values and interests in such a lock-in could cause controversy.[7]

In a related vein, work on 'upstream' public engagement has highlighted the ethical concern that 'the very act of studying and engaging with geoengineering could generate a momentum of its own—an intellectual 'lock-in'—that might also have a dramatic impact'.[34] This is related to the so-called 'slippery slope' argument[35–38] that 'even very basic and safe research ... could be a first step onto a 'slippery slope' toward deployment',[39] or might act to lock-in some options to the detriment of other possible options.[40]

Conversely, the oft-cited argument in favor of research is that without it,

> if and when geoengineering becomes necessary, we will lack knowledge about which approaches are more or less effective and more or less dangerous. So there will be a greater chance that geoengineering efforts will fail or cause serious collateral damage.[41]

However, the implication that research is a neutral activity has been critiqued. For example Jamieson draws attention to what he calls the 'cultural imperative' that holds that if something can be done it should be done, and suggests that this often results in technologies developing 'a life of their own that leads inexorably to their development and deployment'. He draws on the history of medical research to suggests that one of the central reasons for this is that '[a] research program often creates a community of researchers that functions as an interest group promoting the development of the technology that they are investigating'.[36] The report on geoengineering by the US Congressional Research Service made a similar point, by highlighting the fact that '[i]nnovative and entrepreneurial organizations seldom mobilize themselves to put complex technologies "on the shelf"',[42] which may result in a the premature and possibly dangerous promotion and deployment of particular technologies. Similarly a recent report from the Yale Climate and Energy Institute highlighted similar concerns around the slippery slope by pointing to the 'propensity for technologies to be developed once conceived of, and then used once developed'.[38] Another facet of this idea of a 'slippery slope' is the idea that both research and broader civil society or public engagement with geoengineering might have a (dangerous) 'normalizing' effect. A recent article in the Huffington post argued that:

> This insistence that we engage in debate over climate geoengineering is part of the process of "normalization" that seems orchestrated – perhaps deliberately – with the intent of habituating people to the whole idea of climate geoengineering as an option.[43]

Another area of growing interest to assessment of geoengineering, is the role that intellectual property (IP) might play in shaping the development of these technologies.[44] Although not specifically referring to the terminology of 'lock-in', Parthasarathy et al. argue that 'in the absence of any significant regulatory framework, the patent system has become the de facto method of controlling technological development' (p. 7), and suggest that this is likely to shape its development in profound and irreversible ways. They find that in the field of geoengineering,

> 'while relatively few patents have been granted to date, certain trends – including the provision of broad patent language, dramatically increasing numbers of applications, and the concentration of patent ownership – suggest that patents will play an important role in how this technology develops'. (p. 3)

As well as the abovementioned work which is concerned with the various processes that might impact on the future development (and potential lock-in) of proposed geoengineering technologies, the concept of lock-in also features as descriptive of the broader context within which these geoengineering interventions are being discussed—for example, the idea that the world is currently 'locked in to the highest emissions trajectory envisaged by the IPCC'.[45] The concept of carbon lock-in[2,46] has been used to describe the apparent inertia in industrialized highly carbon dependent economies due to the stability of the techno-institutional complexes responsible for the bulk of carbon emissions (encompassing both physical infrastructure and social and cultural practices and institutions). Some geoengineering technologies such as DAC have been examined within the context of carbon lock-in, and it has been suggested that

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these technologies may 'exacerbate carbon-based path dependency and intensify the lock-in of fossil fuels in the near term'.[46] This might also act to 'lock-out' other technologies. Potentially relevant to understanding the types of lock-in processes associated with certain geoengineering technologies is the literature on carbon capture and storage (CCS). For example it has been argued that lock-in of CCS might contribute to fossil fuel lock-in (albeit low carbon), and to a process of lock-out of renewable alternatives.[47,48]

Conversely, geoengineering is seen by some as a way of 'unlocking the mitigation puzzle' and providing a way out of what is seen to be a gridlock. Allenby, for example, has suggested that the UNFCCC process itself is a form of 'cultural lock-in',[49] with existing policy structures (however ineffectual) being unlikely to change because of the institutional and psychological commitments of the participants to the process, and that geoengineering can best be understood as a response to this lock-in. It is interesting then that existing carbon lock-in may well form the basis of an argument both for and against geoengineering, as has occurred in arguments for and against CCS.[50]

Likely as a result of their relatively more developed status, carbon-based geoengineering techniques such as bio-energy with carbon capture and storage (BECCS) have been examined in more detail than solar radiation management methods, particularly with relation to possible impacts on fossil fuel lock-in,[51,52] and there is potentially relevant literature for some carbon based geoengineering techniques to be found in literature on mechanisms of lock-in around CCS.[48,53] It is notable that some of this empirical work on CCS actually suggests that

> there is little evidence at the current time that CCS is 'crowding-out' the alternatives, and it may even be a factor in realising some of those alternatives through sharing underlying technologies. This would suggest that the risk of low-carbon lock-in may be relatively modest.[48]

The concept of lock-in has also featured in debates around biochar, with disagreement apparent about the degree to which biochar should be considered a 'disruptive technology'[54] to incumbent political economic regimes locked into unsustainable pathways, or whether the promotion of biochar and its linkage into carbon markets, might itself result in 'lock-in to routes and styles that favor scale and profit at the expense of local livelihoods and landscapes'.[55]

Ongoing Theoretical Debates

Although the concepts of lock-in and path-dependence have proven useful across a range of disciplines, and are invoked widely within the emerging discussions of geoengineering, there are a number of ongoing areas of debate and contention, and the degree to which path-dependence is understood to constitute a theory is contested.[56] In particular, gathering empirical data about past technological developments to support the theory of path-dependence is problematic, with critics highlighting the difficulty of being able to prove the counterfactual,[57] i.e., the impossibility of gathering empirical material to draw a comparison 'between the current state of the world and what the world would now be like had a different path been followed'.[19] Indeed it has been argued that '[i]n most case study research, path dependence theory is simply unfalsifiable.'[58]

It has also been argued that the original path dependence explanation for the persistence of particular sub-optimal solutions may be 'too simple, too generic'[59] to contribute greatly to understanding persistence in other areas (e.g., public policy), and that other explanations such as first-mover advantage or organizational inertia may be equally or better able to explain persistence.[58]

The issue of the suboptimality or otherwise of path-dependent outcomes is also the subject of long standing academic debate[10,13,60] often fuelled, it has been claimed,[61] by ideological differences. As Arthur argues, the debate about the suboptimality or otherwise of the QWERTY keyboard design (widely cited as the paradigmatic case of path-dependence resulting in lock-in) is not so much about keyboards, but the ideological belief in the power of markets to produce an optimal outcome.[61] Importantly, although much literature has focused on negative outcomes resulting from lock-in, and how it can be avoided, it is also the case that a degree of lock-in is, in many cases unavoidable, and need not always carry negative connotations. As Walker points out:

> In complex fields of technology, commitments can become — and have to become — multifarious, extensive and entangling. Otherwise, nothing can happen. This gives rise to an unavoidable predicament: the very act of 'digging in' commitments makes societies and their institutions vulnerable to entrapment. Not only does 'lock-in' exist, it is an essential but dangerous facet of complex infrastructural innovation.[14]

Given the necessity and inevitability of some degree of socio-technical entanglement or lock-in, Shackley et al. have argued for a differentiation of the concept from deep to shallow lock-in. As they put it:

> lock-in per se is not the problem; it is rather the depth of lock-in which creates problems because deeper

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> lock-in reduces flexibility and increases the 'error cost' (i.e. the cost of a decision which turns out to be based on incorrect understanding) and should be avoided.[48]

Similarly Stirling refers to a 'milder, more routine' form of lock or 'momentum' consisting of 'complex networks of technical, operational, financial, regulatory, educational, cultural, and behavioral factors' and points out that this is generally seen as an essential element in the successful development of new technologies.[62] Indeed, the idea of 'strategic niche management'[63] aimed at helping to induce a socio-technical transition toward sustainability, can be thought of as the process of achieving a desired end by attempting to facilitate a degree of lock-in around a desired novel technology through the protection of a niche in which it can develop. In other words, by 'creating a little bit of irreversibility in the right direction'.[28]

Despite the permanence implied by the metaphor of lock-in, various debates have highlighted that the term 'lock-in' should not be taken too literally, and cannot be understood as a permanent condition.[64] For example some authors have highlighted that one's view on whether a technology is 'locked in' depends substantially on the timescale over which one examines the process. Vergne and Durand thus suggest that arguably 'history did not matter' in the oft cited battle between VHS and Betamax because in the long run both became obsolete, giving way to the use of DVDs.[56] A conceptualization that usefully serves to emphasize processes (rather than the static state suggested by the term 'lock-in') is that of 'emerging irreversibilities'.[28,65] These can be thought of as socio-technical entanglements which over time enable and constrain alignments and activities of persons, institutions, and artifacts.

Debate also surrounds the role of contingency versus the agency of actors in path-dependent processes or lock-in.[56,66] For example, Garud et al., argue against what they see as fatalistic notions of agency implicit in the commonly applied versions of path-dependence in which 'actors become 'locked-in' by self-reinforcing mechanisms into paths whose evolution is determined by contingencies (chance events). Once locked in, actors cannot break out unless exogenous shocks occur'.[66] However, they also argue that the 'heroic' notion of agency found in more entrepreneurial models in which 'actors are driven by 'a logic of control' to effectuate through complex processes' is also inappropriate. This has led these authors to coin the term 'path creation' (rather than path-dependence), in which agency is theorized as 'being distributed and emergent through the interactions of actors and artifacts that constitute action nets' (p. 761). Similarly, Ebbinghaus[67] has suggested the need to move beyond what he considers to be overly 'deterministic and inflexible' understandings of path dependence, in favor of a more developmental understanding of path dependence as structuring of choices that provides a basis for theorizing not just stabilization and inertia, but also the potential for what he calls 'path departure' and institutional change.

Simplistic notions of a linear progression from early to late development of a technology, as it passes through defined stages of path-dependence through to lock-in, have also been questioned. For example, Liebert and Schmidt[68] argue that 'there is no linear time ordering as presupposed by the dilemma (formulated by Collingridge) and its classic linear innovation theory'. They go on to suggest then that although 'the temporal dimension of Collingridge's dilemma might actually exist … the processes are significantly more multi-faceted, non-linear, complex and interactive than the dilemma presupposes' (p. 67). Others have critiqued the notion of the existence of a 'right time' to influence technological development. As Nordmann puts it, '[t]o consider this as a dilemma is tantamount to viewing the present as an obstacle that can and needs to be overcome'.[69] Similarly, Garud et al. have highlighted that 'starting points' for analysis of path-dependent processes are not self-evident because 'the past, present and the future are intertwined, with actors playing an active role in determining what portions of the past they would like to mobilize in support of their imagined futures'.[66]

Technological Assessment: Generic Methodological Challenges

Although in an important sense, all technological assessment shares a concern for possible future impacts of socio-technical development, future states are open to change and are in many cases unknowable.[68] This unpredictability of the future led to Collingridge himself denouncing what he called the 'predictionist approach' (the idea that what is needed to avoid damaging lock-in is simply better forecasting tools), saying that this was a misconception of the problem, since 'harmful effects of a technology can be identified only after it has been developed and has diffused' and 'a whole bundle of unknown factors' will remain.[9] Similarly, Guston and Sarewitz refer to what they call a 'central truth' about the development and proliferation of technology in society, namely 'that this process is largely unpredictable, and thus not subject to anticipatory governance'.[70] They go on to argue that although predicting the social consequences of a technology might be desirable, this goal:

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will never be fully attained, because consequences emerge not from the static attributes of a fully formed technology, but from the complex co-production that simultaneously and continually moulds both technology and social context.[70]

Given the challenge of future prediction, there are a number of methodologies that focus analysis on the present moment (e.g., analysis of the expectations or visions of those people working to develop the technologies in question, or the application of generic sets of indicators to assess a given technology or idea); or look to historical analogs to understand possible parallels. For example, various authors have used indicators of flexibility to assess the likelihood or otherwise of a given technology becoming 'locked-in.' Shackley and Thompson argue that:

[t]echnological (in)flexibility can … be used as a proxy measure of low (high) lock-in. The crucial idea here is that, although lock-in is unavoidable (and necessary), we can do something about the depth of that lock-in; the more flexible are the constituent technologies, the shallower is the lock-in.[48]

Collingridge developed a number of indicators of flexibility[9,71] including high capital intensity, long lead-time from conception to realization, large scale of the production unit relative to the sector, major infrastructure requirements, exaggerated claims about performance, and hubris. He argued that the more of these indicators that are present with regard to a specific technology, the more cautious society should be in committing to adoption of that technology. Others have amended or added to this list, for example, Shackley and Thompson also add a number of what they refer to as 'organization indicators', including closure to criticism and 'single mission outfits'.[48] Similarly the Royal Commission on Environmental Pollution's report on nanotechnology[72] makes use of Collingridge's indicators, and adds an additional indicator of irreversibility in the form of whether or not a technology involves the uncontrolled release of substances into the environment.

While the use of indicators has been usefully applied, one critique of this approach is that—aside from the implicit normative desirability of corrigibility or flexibility in socio-technical development—there is little room for a consideration of what might be considered socially desirable directions for change. This is a generic challenge to the assessment of processes of path-dependence and lock-in, namely, that while this kind of TA is usually understood as being an explicitly normative project,[9] in that it represents an attempt to 'anticipate and ameliorate the down-side impacts of human interventions',[70] work in this area soon encounters the issue that values are not always shared. It is not always the case that 'an unambiguous set of societal goals can be enunciated'.[28] Diverse (sometimes contradictory) goals will be present in any given society at a given moment in time. Indeed technological developments may even change the societal norms by which their impacts are to be judged, they can 'transform our very conception of human beings, human flourishing, and of the proper relationship between human beings and nature'.[73] Given that multiple values and different visions of desired futures exist, there are multiple possible directions for what constitutes desirable technological 'progress.' For example, as Brown puts it:

The future – and its associated meta-concept of 'progress' – emerge through an unstable field of language, practice and materiality in which different groups compete for the right to represent near and far term developments. And like any other contested field, actors engage in such struggles with unequal access to the resources with which futures are manufactured.[74]

These issues raise fundamental questions about the role of assessment. Traditionally, much TA has focused primarily on the notion of risk, utilizing expert-led analytical methods such as cost-benefit analysis, and risk assessment. However, the inadequacy of these approaches to determining the desirability of a given direction of development, or for operating in situations of uncertainty, ignorance or ambiguity, has been the subject of sustained academic critique. For example Stirling argues:

Where there exist divergent socio-political interests and values, it is a fundamental finding in axiomatic rational choice theory that there cannot exist – even in principle – any purely analytical means definitively to reconcile the resulting contrasting preference orderings … This refutes the value of the aggregated quantitative results routinely produced in social appraisal by methods like cost benefit analysis, risk assessment and decision theory.[29]

An overly narrow conceptualization of technology as separate from society has also been the subject of critique which has drawn attention to the hybrid characteristics of technology, incorporating social and discursive elements, and of the importance of social deliberation around the form and direction that technologies take, rather than simply making efforts to minimize impacts. As Macnaghten and colleagues point out, often:

the academic literature has framed technology as 'black-boxed' and well-defined, with an independent

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> asocial logic that results in 'impacts' or 'effects'. Social questions are often narrowly framed as 'impacts' or 'risk' issues, placing the site of social science inquiry firmly 'downstream' of innovation processes.[75]

As a result of this awareness of the social character of technology, the plurality of potential directions of 'progress' and the profound implications for society and democracy of the choosing of particular development paths over others, there has been a turn to greater transparency and reflexivity in processes of TA as evidenced by the development of approaches such as 'real time TA',[70] 'constructive TA',[76] and 'participatory TA'.[77] An important component of these approaches is the need for assessment to be engaged at an 'upstream' moment[69,75] rather than simply considering downstream 'impacts', and to examine the different kinds of visions of the future embedded in particular ideas about emerging technologies, an endeavor sometimes referred to as vision or expectation assessment,[78,79] or the 'forensics of wishing'.[69]

Technological Assessment: Geoengineering-Specific Challenges

A number of large multi-partner, multi-disciplinary projects are currently underway with the remit of assessing geoengineering proposals, including the Integrated Assessment of Geoengineering Proposals (IAGP) and the European Transdisciplinary Assessment of Climate Engineering (EUTrace), and a growing body of work relevant to the assessment of potential processes of socio-technical entanglement—or lock-in—and geoengineering exists. This work includes efforts to trace the historical emergence of the field,[80,81] and to map out the current extent of work in this area,[1] or to explore possible future scenarios in which geoengineering technologies feature.[38] In addition to the generic challenges of TA and the study of processes of lock-in outlined above, there are a number of characteristics that make assessment of geoengineering particularly challenging. This include the difficulties posed by the inherent ambiguity of the term geoengineering; the diversity of technologies that are currently discussed using this terminology and the different ways in which various actors have attempted to categorize these; and the variety of extant framings of geoengineering.

For example, while many authors refer to the Royal Society definition of geoengineering as the 'deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming',[4] the term is still contested, with some authors suggesting that the term is too ambiguous,[82] or that other terms such as 'climate remediation'[83,84] or 'climate management'[85] might be more appropriate. The diversity of approaches subsumed within the umbrella term 'geoengineering' likewise raises significant issues for any assessment of the potential for lock-in. This has led to calls for the term to be disaggregated,[86] and for different approaches to be analyzed individually,[37] or to attempts to group approaches into particular types—such as the much-used Solar Radiation Management (SRM)/Carbon dioxide Removal (CDR) distinction[4]—and for analysis to be carried out with regard to these categories. Rayner has suggested that the CDR/SRM taxonomy could be improved by distinguishing techniques involving so-called 'ecosystems enhancement' from those described as 'blackbox engineering.' The former refers to technologies that 'stimulate or enhance natural processes'[45] such as ocean iron fertilization or SAI, while the latter refers to techniques such as DAC or space mirrors. Another classificatory system draws an ethical distinction between approaches which attempt to remediate or clean up damages, such as DAC (labeled as 'geo-remediation'), and those which aim at 'steering around or repairing anticipated damages', such as SAI, labeled as 'geo-steering'.[87]

The variety of different classificatory systems indicates that no one typology can be considered final or absolute. These struggles around the naming and typologizing of a field are about more than just semantics, and much work in the social and political sciences has emphasized the fact that the act of naming is an important way in which power operates.[88,89] With regard to the naming of an academic discipline or field, work examining the emergence of distinctive fields of 'nanotechnology',[90] and 'synthetic biology'[91] has shown that the act of naming is crucial to the coming together of a 'community of practice'[92] in a particular domain. This delimitation of a named field has important material and political consequences, in that it 'renders more visible, more powerful, and increases the potential to attract funding for, certain forms of work'.[91] Existing, previously unconnected research trajectories may then engage with the new label in different ways—either actively seeking to be incorporated or asserting distinctiveness. In the case of geoengineering, existing research in diverse areas such as climate modeling, cloud physics, aerosols, forestry, or soil science might, from particular vantage points be considered 'geoengineering research', but the cohesiveness of a singular 'field' cannot be assumed. This serves to highlight the problematic nature of assessing geoengineering as a category, and indeed underscores the potential for uncritical assessment to act to reify its object, resulting in geoengineering being framed as a singular technology or set of technologies,

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rather than a very heterogeneous set of discourses, practices, and forms of knowledge. As has been argued to be the case for assessments of biotechnology, there is thus a need for assessment of geoengineering to engage critically with the term itself, to decenter the analysis.[93]

An important part of this process of engaging critically with the label of geoengineering is discourse analytical work examining the framings of geoengineering. A number of such studies have been carried out, highlighting the important ways in which framings are emerging (or being used strategically) and impacting on the development of geoengineering as a distinctive 'field'.[7,94–99] Bellamy et al. in particular have illustrated the ways in which the framing of assessment and appraisal themselves are powerful ways in which particular processes of 'cognitive lock in' might occur, and draw attention to the way in which many assessments of geoengineering to date have created an artificial choice between technologies by focusing on these approaches in contextual isolation, rather than in the context of the wider portfolio of options for tackling climate change.

The existence of diverse framings of geoengineering is related to the existence of diverse societal values in this domain. As mentioned, all TA faces the challenge of incorporating and responding to diverse societal goals and values, and this issue is particularly relevant to the appraisal of geoengineering technologies, and ties into broader debates about the role of technological assessment and appraisal itself – i.e. that it needs to be participatory, deliberative, reflexive, embedded, and so on in order to be able to reflect these pluralities and indeed to avoid reinforcing particular path dependent processes. The elicitation and incorporation of public views and perceptions of geoengineering into governance arrangements is clearly crucially important for any assessment process,[100–103] and yet the very act of engaging publics with the topic of geoengineering is, itself fraught with potential for feeding into path-dependent processes.

The process of 'decentering' the assessment of geoengineering also has a temporal dimension. For example, historical work on weather and climate modification has illustrated that the supposed novelty of geoengineering does not always stand up to scrutiny,[80,81] but is rather best understood as the latest manifestation in a long history of attempts to control the climate. With regard to the study of potential lock-in, the idea that humanity is currently at the frontier of technological development or at an 'upstream' stage, and even the idea of assessing potential lock-in in the future might reinforce this idea of novelty, or act to obscure certain lessons from history. It is also the case that although many of the schemes being discussed have not been attempted to date, history is replete with example of socio-technical developments in other areas that might be relevant to understanding possible patterns of development in geoengineering. The use of historical analogs to examine possible social patterns of responses to technological innovation has been carried out with regard to a number of technologies.[104] Clearly, the choice of analog in any given case is crucial: as Walker points out, generalization from particular historical cases of technological development should be approached 'with caution as the histories of all technologies are sui generis in considerable degree where there is great complexity'.[14] With regard to geoengineering, a number of analogs have been suggested, including nanotechnology, molecular biology, and nuclear science,[42] ecological analogies such as the use of biological control,[105] or human interventions in other natural cycles such as the nitrogen cycle.[106] While some work in this field has been carried out, the use of analogs to better understand the likely social processes at work in different kinds of geoengineering interventions is likely to be helpful. However it may also be the case that there simply are no historical analogs for some of the proposed climate geoengineering approaches, and indeed some may necessitate new ways of thinking and talking about irreversibility. For example, various authors have highlighted that geoengineering through SAI would require extremely long-term commitments in order to function effectively and avoid the rapid heating that would accompany cessation of the programme (the termination effect). However, the use of the term 'lock-in' to describe this situation (see for e.g., Ref 5), expands its usage beyond that which appears in the existing literature, by implicating dimensions of lock-in that are exceptionally extensive and diverse. For example, there appears to be nothing in the canonical examples of lock-in such as nuclear reactors, automobile transport or the QWERTY keyboard design, that resembles the manner and scale of the implication of natural system processes as those postulated in the 'termination effect,' the existence of which has been referred to as leaving the entire earth system vulnerable to 'technological failure'.[107]

CONCLUSION

Given the growth in academic and policy interest in geoengineering, and the profound and (by definition) global scale implications of many of the interventions being discussed in these terms, consideration of potential emerging irreversibilities of various types is timely and crucial. The extensive literature on

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socio-technical lock-in and path dependence provides an important set of theoretical concepts, empirical examples, and methodological approaches that can be helpful in contextualizing contemporary concerns about geoengineering within broader understandings of socio-technical development. This literature provides a wealth of material illustrating the pervasiveness of positive feedbacks of various types (from the discursive to the material) leading to complex socio-technical entanglements which may resist change and become inflexible even in the light of evidence of negative impacts. However, it is also the case that ongoing academic debates have highlighted a number of limitations to the uncritical usage of the terminology of lock-in and path dependence. With regard to path-dependence, critiques include issues around the falsifiability or otherwise of path dependence as a theory and contentions around the suboptimality or otherwise of path-dependent outcomes. With regard to the terminology of 'lock-in', the exceptionalist and largely negative connotation of the term, may act to obscure the more pervasive/unavoidable and often positive nature of socio-technical entanglements of various types.

With regard to assessment, the literature provides a set of methodological tools (such as the use of indicators of flexibility, expectation and vision assessment, and the use of historical analogs) which may prove useful in helping societies to think through possible implications of continued research and development in this controversial area. However, processes of assessment also run the risk of reifying their object, and due attention must be paid to ways in which any assessment can 'decenter' analysis through paying due attention to framing effects. Finally, there may be forms of geoengineering, such as SAI, which (through their implication of natural system processes in the form of the 'termination effect') require fundamentally new ways of thinking and talking about irreversibility.

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