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Ambivalence in calculating the future: the case of re-engineering the world

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Recently, climate engineering and particularly sulphur aerosol injection (SAI) have entered the arena of international climate change politics. The idea behind SAI is very simple: to reflect sunlight and heat back into space by injecting particles into the stratosphere. SAI has the theoretical potential to moderate anthropogenic climate change in a timely fashion and at very low costs but may also cause major environmental harm. Determining the future of SAI will entail dealing with many major uncertainties such as assessing risks, costs and benefits. This paper critically investigates scientific knowledge production under conditions of major uncertainty. It discusses how uncertainty, ethics and social considerations are treated in the SAI literature, which applies techno-economic models. In the simplest studies, important uncertainties are excluded from the models, but the more complex studies include many uncertainties, which may have considerable influence on the results and recommendations. In some cases the modelled results are overshadowed or strengthened by ethical discussions or methodological reflexivity that emphasize uncertainties and model limitations. There seems to be ambivalence between constructing certainty, on one hand, and an awareness of methodological limitations, on the other. Finally, the value of these papers for decision-makers and other concerned groups is discussed.

Keywords: climate engineering; geoengineering; sulphur aerosol injection; modelling; uncertainty; climate change

1. Introduction

The past few years have seen climate engineering (CE)/geoengineering methods, regarded as more or less serious options, gradually enter the arena of international climate change politics and public debate (Scholte et al. 2013). Technologies for reflecting solar energy back into space, i.e. solar radiation management (SRM), have received particular attention. The idea behind these methods is simple: to reflect sunlight and heat back into space by either modifying the earth’s albedo or injecting particles or objects into the stratosphere or space. Some SRM options have the theoretical potential to moderate anthropogenic climate change in a timely fashion and at very low costs (Shepherd 2012). A recurring argument, or emergency framing, for CE is that the climate system has reached, or will soon reach, a tipping point, i.e. a state of self-reinforcing and escalating climate change. In such a case, even radically reducing CO₂ emissions will not have

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mitigating potential, turning SRM into the main option. However, the potential environmental side effects of SRM methods are substantial, including ozone layer depletion, acidification, greyer skies and precipitation disturbances. Furthermore, the positive and negative effects may be unevenly distributed over the globe, adding several ethical, political and governance concerns (Robock 2008; Shepherd et al. 2009; Shepherd 2012).

Making decisions about SRM’s future will entail dealing with many major uncertainties. Aside from a handful of minor field trials, of very limited value when it comes to generalizing, practical experience of SRM is still very limited. The idea of major field experiments has been criticized for potentially involving too many unintended consequences, being inconsistent with international treaties (e.g. the Convention on Biological Diversity and the London Protocol), and probably encountering public resistance. Several researchers have also stressed the extreme difficulty of determining SRM’s impact on climate change, even if large field experiments are conducted (e.g. Blackstock and Long 2010; MacMynowski et al. 2011). Nevertheless, scientific attempts to assess SRM’s future are intense and can be exemplified by extensive appraisals by the Royal Society (Shepherd et al. 2009; cf. Bellamy 2013) and, for the first time ever, inclusion in the forthcoming fifth Assessment Report of the IPCC (2013). Egede-Nissen (2010) and Bellamy et al. (2012) claim that SRM is an archetypical case of post-normal science: the facts are highly uncertain, values in dispute, stakes high and decisions urgent. A common claim made in the public debate on CE, according to Ridgwell (2012), is that economic evaluations must precede any serious consideration of scaling up the technology. Wood et al. (2013) claim that economics plays a significant role in assessing the effects of various policy response strategies and technologies in order to manage climate change. Advocates of applying economic models argue that its capacity to compare costs and benefits makes it uniquely useful for assessments of even complex environmental issues. However, calculations concerning CE have been criticized for their poor reliability, as they involve fundamental uncertainties, unintended consequences and nonlinear dynamics. Moreover, the wide range of probability distributions concerning the effects of SRM on several major natural systems could significantly limit the potential for scientific valuations (Fernow 2012), which would therefore be of limited usefulness to inform decision-making. Heyen (2012) even goes so far as to claim that the uncertainties concerning SRM preclude meaningful results.

Curry and Webster (2011) illustrate how scientific uncertainties are dealt with by the IPCC, and the challenges interrelated to opening up the scientific debate and problems related to politicians justifying decisions based on an inherently uncertain knowledge base. Despite the uncertainties and methodological challenges, theoretical assessments, estimates and valuations of SRM’s pros and cons also constitute an increasingly prioritized research field that might provide important guidance for politicians and decision-makers (Lawrence and Crutzen 2013). Scholte et al. (2013) also show that media frames sometimes originate from CE scientists, hence shaping the public debate. Consequently, the theoretical appraisals of CE matters even though the uncertainties are significant.

This paper investigates scientific knowledge production under conditions of major uncertainty, and implications for policy-making will also be tentatively discussed. It is a critical review of papers conducting cost assessments and valuations of a specific SRM option, i.e. sulphur aerosol injection (SAI). Bellamy et al. (2012) claim that SAI has received an emblematic status in the CE field, and many researchers assert that SAI could have a rapid positive impact on climate change at very low cost. SAI is deemed one of the most feasible options in the major Royal Society report evaluating a range of CE options.
(Shepherd et al. 2009), is the option attracting the most scientific attention (Bellamy et al. 2012) and has been the subject of the most minor field trials and an intense public debate and early social protests, e.g. the SPICE project in the UK (Pidgeon et al. 2013; Anshelm and Hansson 2014).

The paper is guided by Smithson’s (1993) claim that it is important to go beyond studies that illustrate how values influence assessments and deconstructing the implicit ideologies in the scientific methods (e.g. Gardiner 2011). Instead a more relevant, or complementary, starting point according to Smithson (1993) would be to study the (dis) agreement among scientists about what is unknown, how to represent and evaluate that and what to do about it. Hence, the following questions guide this paper:

1. What uncertainties are explicitly presented in the scientific assessment literature on SAI and how are they framed?
2. How are uncertainties treated in the methodological approach to evaluate SAI implementation?
3. What implications do the uncertainties have for the results and recommendations according to the investigated papers?

2. Background

A point of departure in this paper is that uncertainties cannot always be reduced or controlled and instead are negotiable in science (Smithson 1993). Uncertainties can conceptually be viewed at three levels. The first level is basically the awareness of specific uncertainties existing. Two recurring phrases in the literature for characterizing uncertainties that relates to differences in the degree of consciousness of one’s ignorance are ‘what you know you don’t know’ and ‘what you don’t know you don’t know’ – the former refers to parametric uncertainty (or conscious ignorance) and the latter to systematic uncertainty (or meta-ignorance).

Second, Curry and Webster (2011) explain two broad categories of uncertainties related to the characteristics and degree of controllability of the uncertainties; epistemic uncertainties which are associated with imperfections of knowledge and can be reduced by further research and ontic uncertainties which are related to inherent variability and randomness and may be exemplified by variability in the climate systems (e.g. Heyen 2012). Smithson (1993) argues that science has undergone increased pessimism concerning predictability and controllability of nature in the past decades, but also developed methods and strategies for dealing with the uncertainties (e.g. Curry and Webster 2011). Smithson (1993) emphasizes that scientists may disagree about both the nature and extent of what is unknown, how to evaluate it and what to do about it, which may lead to divergent uncertainty assessments, trade-offs and selective (in)attention.

Third, considering scientific knowledge in a wider societal context offers yet another distinction of uncertainties revolving around how and why the uncertainty should be dealt with; technical uncertainty (the extent research techniques are considered to be reliable and well understood) and strategic uncertainty (disagreement about research priorities, significance of problems and how to handle them). Technical uncertainty usually implies strategic uncertainty, but the reverse is seldom the case. Furthermore, political and economic diversity or pluralism strengthens strategic uncertainty. Jerome Ravetz explains that scientists often are requested to undertake problems that the scientists themselves believe cannot be solved. In such cases, Ravetz claims that policy-makers may be deluded by seemingly accurate results, and instead suggests an accurate description of knowledge uncertainties (Smithson 1993).
A few studies emphasize that the choice of method and of factors and variables to include when economically valuing CE is crucial for the results. A specific CE technology can be appraised as having costs that are nearly negligible (e.g. Barrett 2008), while others may conclude that the costs of the same option are of the same magnitude as those of escalating climate change (e.g. Robock et al. 2009). Vast differences can also be found concerning risk appraisals of one specific technology (Bellamy et al. 2012). Sometimes differences in results are traceable not only to methodology. Gardiner (2011) has scrutinized the previously mentioned Royal Society report (Shepherd et al. 2009) and claims that its conclusions are influenced by ethics and values not generally explicitly articulated in the study. Bellamy et al. (2012) and Bellamy (2013) have systematically reviewed published appraisals of CE, primarily considering their appraisal methods, criteria, context frames, foci and reflexivity, raising questions partly overlapping those posed here, but with different analytical ambitions because they primarily investigate the role of framing in shaping appraisal inputs, outputs and epistemic commitments. They analysed 25 articles, criticizing several for lack of transparency and seemingly arbitrary ranking of CE options. To deal with these problems, they recommend not evaluating CE options against only other CE options, which they claim creates a false sense of ‘YES’ or ‘NO’ regarding single methods, but instead appraising CE options relative to conventional mitigation and adaptation options or creating scenarios and explaining in detail how they are constructed.

The present study and Bellamy et al.’s (2012) also differ in empirical focus. I focus on studies appraising CE in relation to conventional methods and/or scenario construction. Another difference is that this study focuses on only one technology, i.e. SAI, which permits systematic comparison of the texts because the differences between the technologies are sometimes fundamental in terms of risks, costs, technical maturity and ethical implications. However, three of the reviewed studies overlap Bellamy et al.’s (2012) sample.

Initially, all published scientific papers dealing with the appraisal of SAI’s costs and climate efficiency in relation to traditional mitigation methods until 2013 were identified.1 The texts, which were found by searching reference lists and databases, are mostly scientific articles published in the past 4 years, but also include working papers. Only texts with extensive appraisals and modelling were selected, and in total, 10 were analysed. Hence, papers based on rough estimations or only qualitative assessments were not selected.

The analysis here was guided by the following questions: How is the technology introduced or contextualized? What methods are applied in analysing the technologies? How are methodological problems and uncertainties dealt with and what is included in the calculations/models? Are the authors reflexive or critical towards the chosen methodology and are uncertainties and ethical considerations discussed? What conclusions and recommendations are presented? In the analysis, attention has also been paid to the communication between the texts; the more recent texts often refer to the older ones, sometimes even critically examining their methods and suggesting and exploring improvements.

3. The appraisals

3.1 Presentation and framing of uncertainties

The reviewed papers frequently acknowledge major parametric uncertainties, or acknowledged unknowns, related to either unknowns in nature, the society’s behaviour
or the models’ limitations. These uncertainties are fairly similar in the papers, but treated differently – for example, if they are considered to be ontic or epistemic (i.e. if they can be reduced with further research or not). In this section, some recurring, but not exhausting number of examples will be illustrated.

Emmerling and Tavoni (2013, p. 3) assert that ‘virtually nothing is known about potential side effects along many dimensions’; nevertheless, they have the explicit aim to evaluate SRM (SAI) focusing explicitly on the uncertainty of its effectiveness. In line with that, Goes et al. (2011) initially criticize Barrett (2008), who has stated that SAI is ‘incredibly’ inexpensive for committing to an uncritical view of SAI’s risks and uncertainties. They claim that previous research has disregarded these aspects, enabling SAI to be described as significantly less expensive than conventional mitigation technologies. Goes et al. (2011) claim, in line with most of the reviewed papers, that a few important uncertainties are often neglected or downplayed: (1) early termination; if SAI is not maintained for the long term, its reflective capacity will ebb, resulting in rapid and dramatic temperature increase with environmental effects worse than those occurring without any climate mitigation or management; (2) SAI can deplete the ozone layer; (3) SAI does not counteract ocean acidification and (4) SAI can disturb precipitation, such as the monsoons.

In cooperation with different co-authors, the economist Moreno-Cruz has written three articles on the economics of SAI in a wider societal context, applying the dynamic integrated climate-economy (DICE) model. In the first article, Moreno-Cruz and Smulders (2010) seek to analyse SAI’s costs and impact on climate politics. They investigate, for example, the circumstances in which SAI can replace or complement conventional options and consider what level of SAI is optimal. To provide answers, they focus on SAI’s environmental risks, for example, precipitation disturbances, acidification, ozone depletion, health effects and unilateral action. SAI is deemed to be efficient if:

With respect to the net effects of geoengineering, it is expected that the benefits from the cooling effect of geoengineering outweigh the costs from changes in droughts and precipitation. Although, this outcome is extremely uncertain, since it is based on computer simulations rather observed in real data /.../ (Moreno-Cruz and Smulders 2010, p. 13).

However, Moreno-Cruz and Smulders (2010) claim a better understanding of the uncertainties are still attainable, i.e. the problem is considered to be an epistemic uncertainty.

In Moreno-Cruz’ second article, it is claimed that the input data are associated with significant uncertainties and that the model has limitations when it comes to predicting regional precipitation, i.e. technical uncertainties. The authors have also previously mentioned biases due to the idealized treatment of SAI, and an assumption of linearity concerning the impact of radiative forcing on climate response (i.e. climate sensitivity), which is a recurrent ontic uncertainty in all but three papers that has to be handled. One potential deduction following these methodological limitations is that the reliability of the study may be questioned. The authors instead emphasize that uncertainties will remain in the future, even when the knowledge gaps have been reduced; hence, uncertainties are unavoidable but should not constitute a barrier to modelling-based policy guidance (Moreno-Cruz et al. 2012). In the third article, Moreno-Cruz and Keith (2012) present SAI as ‘quick and it is cheap’ and technically feasible, but also involving great uncertainties and introducing novel risks. The specific aim is to investigate the trade-offs between the pros and cons of SAI in a ‘cost-minimizing optimal decision framework’, described in the following section, which introduces a few challenges related to strategic uncertainties, e.g. which problems should be prioritized, what is the significance of the problems and how should they be dealt with.
Regarding uncertainties treated using the methodological approach, Moreno-Cruz and Keith (2012) point out that the recently mentioned optimal global policy demands a centralized decision-maker that minimizes the global mean temperature even at the expense of regional inequalities. Therefore, this approach circumvents the main idea of increasing the level of SAI only until one region starts to become worse off. Furthermore, the model does not address uncertainties concerning the risk of early termination, for example, as Kosugi (2012) below does, or non-monetary environmental values. These aspects are mentioned by Moreno-Cruz and Keith (2012), but they still claim ignoring these aspects do not negate the value of the paper. Moreno-Cruz and Keith (2012) conduct the analysis in two steps. First, given that the decision-makers face uncertainty regarding climate sensitivity, four possible futures are presented. All four futures assume that the decision-makers ‘learn the true sensitivity of the climate’ (p. 3). Hence, a matter of ontic uncertainty is regarded as resolved, even though this uncertainty is presented as a fact in the introduction of the paper, which states: ‘this uncertainty is irreducible over a timescale of decades’ (p. 2) (see also Emmerling and Tavoni 2013). In the second step, learning – gleaned from gradual small-scale implementation, which reduces the uncertainty concerning SAI – is either introduced before abatement decisions, before SAI implementation decisions, or not at all. In three of the four cases, the uncertainty concerning SAI is assumed to be resolved. Due to the climate sensitivity, SAI may be regarded as a sort of insurance, i.e. if climate damages turn out to be massive, SAI can be implemented quickly. On the other hand, the damage caused by SAI is unknown and, taken together, one could claim that the hypothetical outcomes of these superimposed uncertainties make the situation even more complex to model. Hence, the parametric uncertainties are considered to be resolved either by time or by reducing the technical uncertainties in this case, no matter if they are characterized as epistemic or ontic.

Goes et al. (2011) endeavour to include the identified risks as well as climate sensitivity in a proven model (DICE) and run optimizations also considering conventional methods, to conduct a more realistic appraisal. The authors’ discussion of methodological weaknesses, or technical uncertainties, includes a brief critical review of DICE shortcomings. The discussion continues by citing the ‘deep uncertainty’ of climate sensitivity and uncertainties are acknowledged in the climate science, model and technology per se. Attempts to manage these uncertainties primarily involve the construction of many potential outcomes, in other words, sensitivity analyses. The economic damages due to SAI are, on an explicitly subjective basis, attributed values of 0–2% of global gross national production (GNP). In the next step, several scenarios are constructed: (1) business as usual; (2) optimal climate management without CE; (3) only SAI but (a) interrupted or (b) sustained and, finally, (4) an optimal mix of SAI and conventional methods. If the uncertainties are neglected, Goes et al.’s results coincide with Barrett’s (2008), i.e. SAI is efficient, but when uncertainties are included, the SAI option becomes the worst. However, both the probability that SAI will be interrupted and the extent of the environmental damages are described as deeply uncertain. Despite the ontic uncertainties, a cost–benefit analysis (CBA) is performed and the authors state, citing precise numbers, that SAI is only efficient if it fulfils two requirements from a CBA perspective: the probability of premature termination cannot exceed 15% and economic damages of SAI cannot exceed 0.6% of global GNP. Admitting that these numbers do not provide robust guidance, the authors continue with a longer ethical discussion that later guides the study’s conclusions and recommendations.

The modeller Kosugi (2012) agrees with Goes et al. (2011) that interrupted SAI might be worse than doing nothing at all (i.e. the business-as-usual scenario), but emphasizes that the probability of premature termination cannot be calculated. Consequently, conducting
CBAs is not productive in this case, though a better understanding of SAI is essential, Kosugi claims. Accordingly, Kosugi (2012) seeks to quantify the problems identified by Goes et al. (2011). To circumvent the dilemma of analysing aspects that are ontic and not calculable, Kosugi (2012) instead claims to illustrate the conditions under which SAI is acceptable, but without estimating the probability of particular outcomes. In accordance with previous studies, Kosugi assumes that the costs of SAI are very low as long as uncertainties concerning environmental risks are neglected and SAI is maintained for the long term. As these risks are, according to Kosugi, impossible to calculate, especially because risk aversion varies across countries and individuals, the author introduces the ‘fail-safe principle’, i.e. the tolerable amount of SAI to use.

The principle implies avoiding the risk of abrupt rebound warming in the event of premature SAI termination. The amount of SAI is restricted to a risk-free level of implementation that will not contribute to more than +0.2°C increase per decade or more than 2°C in the long term. The objective of the modelling exercise is to calculate the optimal level within these boundaries. Risks other than temperature change are not ruled out, but claimed to be impossible to predict. Therefore, four damage levels between 0% and 2% of global GNP are estimated. Running the model indicates, for example, that if the damage totals 2% of global GNP, SAI should not be applied, while estimated damage totalling 1.5% of global GNP suggests postponing SAI by a few decades and implementing it at a smaller scale (Kosugi 2012).

The industrial economists Bickel and Agrawal (2013) are critical towards the paper by Goes et al. (2011). They hypothesize that Goes et al.’s (2011) rejection of SAI was based primarily on their framing of SAI, rather than on the technology per se. They test the hypothesis by replicating Goes et al.’s (2011) method, except for altering a few variables such as discount rates. The scenarios are also altered because, according to Bickel and Agrawal (2013), they present an unfavourable framing. For example, Bickel and Agrawal disqualify Goes et al.’s (2011) option of implementing SAI without any other climate measures, which they claim is unrealistic. Furthermore, Goes et al. (2011) are criticized for comparing SAI with the option of fundamental CO₂ reductions – an option that is superior a priori. In addition, Goes et al.’s (2011) framing is that SAI – but not any conventional options – might be interrupted; Bickel and Agrawal claim that all options might be interrupted.

In line with Bickel and Agrawal (2013) and Gramstad and Tjøtta (2010) conclude that SAI may pass a CBA test and lower the total costs of managing climate change. A limited methodological critique related to technical uncertainties is presented, identifying, for example, that the DICE model in this case presupposes effective market allocation of capital and labour and efficient global environmental politics concerning, for example, global emission trading systems. The main criticism, however, concerns how SAI may be viewed by society, i.e. strategic uncertainties. Gramstad and Tjøtta (2010) also raise the concern that voters might reject SAI despite an awareness of positive CBAs. Similarly, Moreno-Cruz and Smulders (2010) argue that the costs must be weighed against the benefits and, based on that calculation, the optimal proportion of SAI is calculated in relation to the conventional methods. However, if the CO₂ concentration passes a certain threshold, costs will instead increase due to ocean acidification. For that reason, there seems to be a balancing act relying on beliefs that nature and its responses to SAI are sufficiently predictable and that humanity, helped by technology and scientific knowledge, will be able to calibrate it. The authors modestly conclude that it may be too risky to initiate large-scale SAI and that conventional methods can never be completely replaced by SAI. Nevertheless, they maintain their position that SAI at least has the potential to reduce the total costs of stabilizing temperature levels.
The economist Sterck (2011) has replicated Moreno-Cruz and Smulder’s (2010) method, but altered a few central assumptions, which, according to the author, makes the model more realistic. He claims that the previous literature on SAI and costs disregards three important differences between conventional abatement and SAI, i.e. SAI requires sustained research and large initial investments, but acts faster than does abatement, and introducing these aspects into a model is the aim of his paper. Contrary to what is claimed in most of the other studies, Sterck (2011) does not assume that SAI is inexpensive. In the model, each country makes rational choices and optimizes the mix of emissions reductions and SAI based on information on net benefits and costs. Consequently, information that SAI works reduces the efforts to reduce emissions and increases the use of SAI. In the simulation, SAI is implemented intensively over a short period, giving rise to a sharp lowering of global temperature, which may in turn have dramatic effects if ecosystems are unable to adapt quickly enough, according to Sterck (2011). To conclude, SAI may create intergenerational injustice because it transfers abatement costs to future generations (cf. Goes et al. 2011; Bickel and Agrawal 2013; Goeschl et al. 2013).

A subsequent article by Moreno-Cruz et al. (2012) investigates intra-generational justice, because regions can be affected differently by the side effects, and develops a model accounting for the potential effectiveness of SAI in compensating for climate change. Some regions will only be affected negatively, while others will enjoy all the benefits, raising a dilemma concerning risk trade-offs. Moreno-Cruz et al. (2012) measure SAI’s effectiveness according to two indicators/criteria, i.e. variability-normalized regional temperature and variability-normalized regional precipitation. They also introduce three social objectives, i.e. ethical perspectives: (1) egalitarian (weighted by regional population); (2) utilitarian (regional economic output) and (3) ecocentric (regional area). Depending on the chosen social objective, the globally optimal level of SAI will differ. If more than one social objective is considered at a time, the compromises lead to lower optimal global SAI levels. The modelling allows positive impacts in one region at the expense of another region, which the authors feel is unsatisfactory. The trade-off dilemma is resolved by introducing the Pareto improving perspective, that is, choosing the level of SAI that minimizes damages for all regions without making any worse off. This method reduces the optimal amount of SAI to 56% of its potential total, in other words, SAI compensates for 56% of the CO2e-induced damages worldwide.

The identified major uncertainties are similar in most of the papers and also the initial characterization of them as either epistemic or ontic uncertainties. The scientists also apply similar methods, primarily the DICE model (4 of 10) or construct simple models (5 of 10), but there are major differences concerning the framing and treatment of the technical uncertainties, for example if particular adjustments of the methods are considered to be reliable and also having the potential to satisfactorily handle ontic uncertainties. The differences between the papers increases further when analysing the strategic uncertainties, possibly because the chosen methods do not provide any firm guidance on how to manage uncertainties that primarily are exogenous to the models, i.e. most ethical, social and political aspects.

3.2 The uncertainties implications for results and recommendations

Linnér and Wibbeck (forthcoming) have reviewed recommendations in peer-reviewed journals and discovered that only 7% rejected CE and no more than 2% unconditionally advocated deployment. A majority (89%) of the papers ended in some kind of explicit recommendation, most commonly that more research or experiments were needed, but also emphasizing the
importance of exercising caution. This pattern seems to be congruent with the findings in the present study (see also Bellamy et al. 2012), and with Crutzen’s paper in 2006 on breaking the geoengineering research taboo and call for coordinated scientific research.

Kosugi (2012) calculated that the economic gain of the ‘fail-safe’ levels of SAI, as previously explained, throughout the century only contribute 0.4% lower total costs for managing climate change, though other uncertainties related to environmental risks are still not considered in the model. He concludes that SAI does not seem desirable when uncertainties concerning SAI termination and related economic damages are acknowledged, and instead advocates extensive emissions reductions, even if SAI is available. He also stresses the importance of improving the models, primarily by applying higher geographical resolution and including additional environmental risks to provide a better basis for decision-making. However, Kosugi (2012) presents a fairly extensive discussion of the limitations and caveats of economic modelling. For example, the limitations of the DICE model are mentioned, and also the exclusion of socio-economic aspects and technological development.

However, a few studies do try to tackle some of these issues. Sterck (2011) says that it is troubling: SAI would offer net benefits to current generations, while future generations would inherit more pollution and may be forced to continue implementing SAI, thus experiencing even more of its side effects. The main recommendation is that there is an urgent need for a research agenda paired with large-scale experiments testing promising methods. So, despite the criticism, it is claimed that SAI might be a useful option and that trustworthy knowledge should be gained to inform the precise implementation that is ethically acceptable in the near term. SAI can be developed soundly, it is claimed, but how this is to be done is not explained in detail. But, there are also more skeptical papers in the review.

Referring to the immorality of transferring risks for future generations to deal with, Goes et al. (2011) rule out SAI. Though SAI may reduce present costs, it increases future costs, creating a situation of both higher costs and escalating climate change (cf. Goeschl et al. 2013). The ethical discussion also takes account of the DICE model. Goes et al. (2011) cite the inherent normativity, i.e. consequentialist discounted utilitarianism, which evaluates consequences based solely on their discounted monetary value. They claim that another value basis could well result in completely different outcomes. One concluding remark is that the ontic uncertainties legitimize making no decisions about SAI implementation, unless the situation is acute. Remarkably, the modelled results are overshadowed by an ethical discussion and methodological reflexivity that emphasize both strategic uncertainties and technical uncertainties related to the model limitations. But, Goes et al.’s (2011) critical stance and conclusions were already criticized in 2012 by Bickel and Agrawal (2013) in the very same journal in which their article was published – Climatic Change.

By implementing a few modifications to Goes et al.’s (2011) model, Bickel and Agrawal (2013, p. 15) claim that SAI will perform much better in the CBA, which had a negative outcome in Goes et al. (2011):

Differing and we believe more reasonable framings of geoengineering use result in nearly the opposite conclusion: GEO [i.e., SAI] may pass a cost–benefit test over a wide range of scenarios regarding (i) the probability it would be abandoned, and (ii) the economic damage caused by its use.

These claims are emphatically presented in the abstract without reservations. However, in the paper itself, the authors declare that their assumptions concerning environmental damages might prove to be underestimated and might increase nonlinearly with SAI deployment. This article also displays awareness of the fact that significant uncertainties may influence the results, though the authors primarily highlight the framing
effect to support their assertion that SAI may be efficient and prevent future damage better than conventional options. This claim, which is weakened considering the methodological limitations the authors mention, is instead supported by an ethical discussion. According to Bickel and Agrawal (2013), not implementing SAI is unethical because it entails transferring risks to future generations, prompting the authors to apply a lower discount rate than did Goes et al. (2011). Therefore, while this article advances a serious criticism due to technical uncertainties, explaining why its results are questionable, it ends by asserting, strengthened by ethical considerations, that the results are relatively trustworthy in any case. This argumentation is opposed to Gramstad and Tjøtta (2010) who declare that SAI passes a standard CBA, but not if strategic uncertainties are considered.

Because the uncertainties exist today and the costs of postponed SAI implementation are relatively modest, Gramstad and Tjøtta (2010) propose postponement because it provides more time to scrutinize the uncertainties. The governance obstacles, i.e., the necessity of long-term, stable global management for 200 years, are highlighted in a four-page discussion of issues beyond the CBA. This represents yet another case of downplaying the modelling results by citing aspects exogenous to the models, in this case, societal rejection of SAI and deficient global governance. This conclusion is similar to Moreno-Cruz and Smulders’ (2010) who modestly conclude that it may be too risky to initiate large-scale SAI and that conventional methods can never be completely replaced by SAI. Nevertheless, they maintain their position that SAI at least has the theoretical potential to reduce the total costs of stabilizing temperature levels, even if major regional damages are created.

In the conclusions and abstract, Moreno-Cruz et al. (2012) emphasize that achieving a high global optimum can compensate for considerable regional-level damages, for example, affecting the water and food supplies for two billion people. Adjacent to these statements, some notes on methodological limitations are presented. The authors’ final words are:

However, the type of difficulties in designing an optimal SRM policy that are illustrated by this analysis will certainly persist even as our knowledge of the effects of SRM is refined. This fact suggests that a simple model like the one we present here will remain relevant. (Moreno-Cruz et al. 2012, pp. 660–661)

The approach considers only a narrowly defined utilitarian ethical perspective. Environmental risks, moral hazard, premature termination of SAI, learning effects and deeper social dimensions are still not thoroughly treated according to the authors. In the later article, Moreno-Cruz and Keith (2012) consider several of these aspects when investigating how optimal policy would be influenced by SAI’s side effects, in light of climate sensitivity, and may be recommended for implementation.

Moreno-Cruz and Keith (2012) treat these major technical and strategic uncertainties in the modelling by assuming a large number of outcomes and combining them in various constellations; the model indicates, among other things, that the level of SAI is always higher in cases of high climate sensitivity and ‘that it is still optimal to implement high levels of SRM [SAI] even if the marginal damages from SRM [SAI] are higher than those of climate change’ (p. 10). Moreno-Cruz and Keith (2012) call this result ‘counter-intuitive’, but claim that it emerged because it is very valuable to have SAI available as a quick-response option. This can be interpreted as promoting SAI as an insurance policy. An often, recurring criticism articulated in the CE debate is the moral hazard argument: If SAI is perceived to have the potential to quickly reduce global temperature, it may encourage reduced effort on the main option (i.e. mitigation) to reduce climate change. This result, that SAI is a warranted option, is based on the assumption that the damages caused by SAI may either turn out to exceed those of climate change or that it is equally possible that the
damages caused by SAI may equal those of climate change or be non-existent. In the final section, Moreno-Cruz and Keith (2012) touch on technical uncertainties, noting that the model is highly simplified and does not consider issues such as distributional effects. Despite all the model’s limitations and acknowledged uncertainties, the authors claim that the main result is unaffected: SAI is valuable for managing climate risks because it can be implemented quickly in case of a ‘climate emergency’.

In the reviewed papers, the authors’ conclusions are often conditioned by assumptions concerning environmental risks, ethical concerns or political constraints. Only a few papers maintain that their results are robust. The farthest-reaching recommendation suggests further research or keeping SAI as plan B. The three articles by Moreno-Cruz and colleagues are among the more supportive of the future deployment of SAI, even though they are restrictive being about explicit recommendations, and have received critique for their SAI-supportive stance. All the papers struggle with uncertainties concerning the lack of scientific knowledge of both climate change and SAI and to various degrees reflect on how and when these aspects should be calculated, valued and weighed against other values. In the final section, the most interesting findings will be discussed and contextualized and finally, the article ends with a tentative discussion on wider societal value of these studies.

4. Concluding discussion

The dominant framing of CE revealed in Bellamy et al.’s (2012) review is confirmed in the present study. SAI is presented as a potential solution to an acute global problem that humankind might be unable to manage using conventional and proven methods. SAI may be quick and inexpensive, but it has potentially huge environmental side effects that may incur major costs. More research is needed and better models may yield insight into optimal levels of SAI implementation given a wide range of underlying assumptions. However, major uncertainties are generally acknowledged and managed in the analyses in very different ways. There is a general lack of unconditioned enthusiasm for development. SAI is seldom described as a necessity, at least not without major reservations being made explicit. The conclusions are often presented with major reservations, about the methods and assumptions. There are still major resemblances to Crutzen’s (2006) seminal paper in the literature regarding both framing of the problem and recommendations.

Development enthusiasm like that surrounding nuclear power in the 1950s, or more recently carbon capture and storage technologies in the 2000s, cannot be traced in this review. There are neither firm statements concerning a ramp-up of SAI nor of other societal benefits as a consequence of its deployment. This picture also seems congruent with how CE is depicted by experts in the mass media (Anshelm and Hansson 2014). The scientific debate on SAI does not seems to have closed down on specific conclusions or recommendations regarding SAI, which also overlaps Scholte et al.’s (2013) analysis of the mass media debate. On the other hand, Bellamy et al.’s (2012) claim that the framing effects close down upon particular sets of problem definitions, which privileges certain decision options and contribute to certain governance commitments. However, the farthest-reaching, and also most frequently recurring (6 of 10), modelling-based recommendation that is stated with confidence is that more research is needed to reduce the uncertainties. Though there seems to be ambivalence concerning the ability of science to reduce these scientific uncertainties, even uncertainties that are explained to be ontic are sometimes assumed to be possible to handle by time. Smithson (1993) explains that traditional Western science follows the ideal to reduce, eliminate or banish ignorance or uncertainty – they are unwanted and considered to be possible to master. On the contrary,
more modern scientific approaches encourage recognizing, negotiating and analysing uncertainties in order to find ways to make decisions in spite of uncertainties. The ambiguity in the texts reflects parts of both these ideals.

The texts’ authors highlight several uncertainties and knowledge gaps, but they treat them in different ways. In the simplest studies, most strategic uncertainties are excluded from the models, but the more complex studies include many strategic uncertainties such as politics, valuation of environmental damages, ethics and various assumptions regarding the likelihood of critical events, which may have considerable influence on the results and recommendations. Van der Sluijs (2005, p. 90) explains that ‘By normalizing the post normal along these lines, the classic paradigms of Decision Support striving for optimization of expected utility as rational risk management strategy can be maintained’. But, these studies are sometimes so complex that the results are difficult to interpret; moreover, because they superimpose major uncertainties, their conclusions are particularly uncertain. How, then, does the reviewed research relate to these seemingly overwhelming uncertainties? One reasonable consequence of the uncertainties is that the results may have very limited, if any, value, and that the benefits of modelling CE may be disqualified as Fernow (2012) and Heyen (2012) have discussed. These drastic conclusions are not forwarded in the modelling discourse; instead, it articulates a firm belief in the potential to improve the models and that at least a few insights have been provided – in some cases, even very important and robust ones.

About half of the papers apply the DICE model, and its limitations and framing effects are sometimes mentioned or even specified, i.e. the technical uncertainty. Botzen and van den Bergh (2012) investigated the DICE model’s sensitivity to climate damage, i.e. the economic damage function. They claim that the discount rate has impact on the ‘optimal policy’, but in particular DICE seems to be very sensitive to the damage function. The technical uncertainties in DICE due to ontic uncertainties are in many cases acknowledged in the reviewed papers, but seldom addressed methodologically. Maybe DICE is so accepted that choosing this particular model and defending its weaknesses seems needless, DICE provides a standardized way of reducing or managing uncertainties, but as Smithson (1993, p. 147) claims, admitting uncertainty ‘can enhance one’s reputation for scientific cautiousness or sobriety’. However, Bickel and Agrawal (2013) illustrate that DICE’s discounting rates greatly increases the optimal level of SAI, while other researchers emphasize that the model is very simplistic and has inherent ethical frameworks, and excludes important ethical or social aspects that influence the modelled results (e.g. Goes et al. 2011). Some of the papers excluded ethical and social aspects and this may either strengthen or weaken the results; hence, the choice per se of DICE does not determine the assessment’s outcome in terms of SAI’s attractiveness.

About half the studies present reflexive discussions of societal and ethical issues and framing effects not included in the modelling. Remarkably, these discussions are in some cases even allowed to outweigh the modelling results and provide either a more CE positive or negative picture. In these cases, the qualitative discussions, which are based on neither empirical data nor previous research, may even disqualify the quantitative results. The methodological reflexivity ranges from nearly nonexistent to far-reaching. In some cases, the authors discuss the ethical imperatives in their studies and state that their choice of ethical perspective and model influenced the results. Important strategic uncertainties such as inter-generational issues, inequality between continents and the valorization of environmental damage are in those cases deemed unsatisfactorily assessed. Nonetheless, these aspects are often included in the modelling; in fact, most of the studies explicitly aim to analyse at least some of these issues’ impact on the assessment of SAI. Most of the papers translate different values and convert them, generally without reflection, to monetary values, such as per cent of global GNP. The models imply a world that can be precisely measured, adjusted and optimized.
and that leaders are both able and willing to respond to this knowledge. Paradoxically, however, the reflexive parts of these studies do not seem to share this world view. Two very conflicting rationalities live side by side in the texts, but the papers’ discussions and conclusions seem to be based on one or the other of them seemingly arbitrarily (cf. Markusson 2013).

Adding more complexity to the models does not increase their accuracy; on the contrary, I claim doing so may make them more difficult to interpret, especially by one of the main target groups – policy-makers. But also, as Bellamy (2013) claims, opening up CE assessments for example policy-makers by revealing the complexities and uncertainties that are often reduced might also make a more uneasy reading. Because the reflexive discussions are seldom mentioned in the abstracts and conclusions of the papers, the results may seem more certain than if the authors’ reflexive considerations were emphasized. Moreover, Smithson (1993) argues that policy-makers are better off with detailed discussions on how extensive the uncertainties are than seemingly accurate assessments.

Considering the models once more, what is the value of these papers for decision-makers and other concerned groups? Possibly, highlighting scientific uncertainty provides an argument for further SAI research, especially because the results so far indicate that SAI is a plausible future option. Gradual small-scale implementation may in a few cases, with some reservations, provide knowledge trustworthy enough to inform decisions regarding full-scale implementation. However, invoking the ‘slippery slope’ argument, Hulme (2012) claims the message about more research is more harmful than might seem: previous research has demonstrated that when the development of a new technology starts, the plausibility of full-scale implementation increases. With time, research and implementation may overlap. Yet another answer could be that the studies demonstrate that SAI’s uncertainties cannot be managed no matter how intense the research efforts. Hence, these studies may be an argument for early rejection of the SAI idea and stronger commitments to mitigation. Finally, I would claim that the studies do not provide a trustworthy basis for an economic assessment of SAI – in fact, in many cases, providing such a basis does not seem to be the authors’ main goal. Superimposing complexities and uncertainties provides a patchwork of potential outcomes, which in turn are difficult to assess. Rather, the goal seems to be methodological development and/or strengthening an a priori personal belief concerning the desirability of SAI and possibly also the case for more SAI research. The interpretative flexibility of these studies seems to justify further research into how the modelled results and eventual recommendations are constructed the following years – a focus that is highly relevant considering that CE is assessed in the forthcoming IPCC main report and important decisions have to be made the coming years.

Finally, another answer can be found in studies on the intersection between science and policy. Van der Sluijs (2005) explains four strategies for coping with uncertainties in the science-policy interface and introduced the concept ‘uncertainty monster’ for analysing how the scientific community may respond to uncertainties that are difficult to ‘tame’. As previously stated, I claim there is a tension in the reviewed literature between on one hand acknowledging an ontic uncertainty and on the other, the ambitions to resolve these uncertainties by either reducing the technical or strategical uncertainties, hence turning it into an epistemic uncertainty. This tension creates an ambiguity concerning recommended strategies on how the society should treat the uncertainty (monster). The first strategy is ‘monster exorcism’, i.e. advocating more research in order to reduce the uncertainties: ‘Uncertainty simply does not fit within symbolical order where science is seen as the producer of authoritative objective knowledge’ (Van der Sluijs 2005, p. 89). But Van der Sluijs (2005) argues that when chopping a head of the monster several new monster heads tend to grow, as on the Hydra, because of unforeseen complexity. Another
strategy is ‘monster assimilation’ and is about adapting the monster in a flexible and constructible way and admitting that consensus about the truth concerning the uncertainties is unlikely to be achieved, given the post-normal situation. Instead the aim is to head for transparency of different positions, the ever-changing nature of the monster and to learn to live with both the ambiguity and pluralism inherent in risk assessments.

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Note
1. See Appendix A for a table of the reviewed papers and a simplified overview of their methodological approaches.

References
Goeschl T, Heyen D, Moreno-Cruz J. 2013. The intergenerational transfer of solar radiation management capabilities and atmospheric carbon stocks. Environ Resour Econ. 56:85–104.


### Appendix 1. Examples of approaches and uncertainties.

<table>
<thead>
<tr>
<th>Model</th>
<th>Epistemic parametric uncertainties</th>
<th>Ontic parametric uncertainties</th>
<th>Ethical/social discussion influencing results</th>
<th>Results</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bickel and Agrawal (2013)</td>
<td>DICE. Claim that DICE’s discounting rates favours SAI and the model has framing effects</td>
<td>Explicitly assuming mean values or ‘best estimates’ for several parametric uncertainties, e.g. climate sensitivity</td>
<td>Nonlinear damage caused by SAI. Probability that SAI is aborted. Future emissions</td>
<td>Both using and not using SAI passes risks to future generations. However, this comment is not related to the results. Ethical arguments support results</td>
<td>Using more reasonable framings of SAI (than Goes et al. 2011) results in SAI passing a cost–benefit test over a wider range of scenarios</td>
</tr>
<tr>
<td>Emmerling and Tavoni (2013)</td>
<td>The integrated assessment model WITCH</td>
<td>Uncertainties concerning CE’s effectiveness and damages resolved by time – the true state assumed to be learned in some scenarios</td>
<td>The levels of certainty regarding highly uncertain variables are altered (e.g. CE’s damages and climate sensitivity)</td>
<td>Public acceptance of SAI, governance and ethical issues may influence SAI’s effectiveness, but are explicitly excluded from the analysis</td>
<td>The uncertainty about SAI’s effectiveness implies that the world should prioritize significant mitigation</td>
</tr>
<tr>
<td>Goes et al. (2011)</td>
<td>DICE. The model is claimed to make explicit value judgements and favours a particular ethical framework</td>
<td>A function of the ontic uncertainties (i.e. SAI damages and probability of intermittency) is created</td>
<td>Risk of intermittent SAI. SAI’s economic damages. Cost of CO₂ abatement. Climate sensitivity.</td>
<td>SAI fails the principle of intergenerational justice because it creates short-term benefits and transfers risks to the future. The ethics in the DICE model influence the results (it downplays future risks)</td>
<td>SAI can fail a cost–benefit test and transfers risks to future generations. The effectiveness of SAI rests on deeply uncertain estimates</td>
</tr>
<tr>
<td>Reference</td>
<td>Description</td>
<td>Climate sensitivity revealed by future generations</td>
<td>Rational courses of action for current generations in relation to future generations are being modelled</td>
<td>Abatement may be higher when SAI capabilities are developed, and the 'moral hazard' argument is weak</td>
<td>More economic research addressing SAI and intergenerational issues</td>
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<tr>
<td>Goeschl et al. (2013)</td>
<td>The authors develop ‘the simplest two-generation model’</td>
<td>×</td>
<td></td>
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<tr>
<td>Gramstad and Tjøtta (2010)</td>
<td>DICE. The model presupposes effective market allocation of capital and labour and efficient global environmental politics</td>
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<tr>
<td>Kosugi (2012)</td>
<td>DICE. The model has weaknesses, e.g. is simplified and only treats mean surface temperature at the global scale</td>
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</table>

Assumes one specific value for climate sensitivity. The positive impacts of SAI based on a survey of literature data, but economic damages are neglected.

If SAI would be sustained through its planned project time. Climate sensitivity. Damages due to CE. Future socio-economic aspects such as population increase and technological progress are explicitly omitted.

Because of the uncertainty regarding the society’s ability to sustain SAI the ‘fail-safe’ approach is applied, e.g. a level of SAI that avoids severe climate damages if terminated.

If the risk that SAI is terminated is non-existing SAI would be less expensive than mitigation. If there is a risk of termination the recommended level of SAI is reduced drastically.

Sharp reduction of CO$_2$ is necessary even if SAI is available (and the termination risk is taken into account). Research into risk preferences, SAI related conflicts and moral hazard and the models need higher geographical resolution.

(Continued)
### Appendix 1 – continued

<table>
<thead>
<tr>
<th>Model</th>
<th>Epistemic parametric uncertainties</th>
<th>Ontic parametric uncertainties</th>
<th>Ethical/social discussion influencing results</th>
<th>Results</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moreno-Cruz and Smulders (2010)</td>
<td>Construct a simple model of climate change economics</td>
<td>×</td>
<td>Benefits from SAI’s cooling effects and damages</td>
<td>×</td>
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| Moreno-Cruz and Keith (2012) | Construct a simple cost-minimizing optimal-decision model/framework | Social costs, SAI damages. Climate change sensitivity and damages (irreducible uncertainties over time-scale of decades but can be fully reduced by research). Random climate sensitivity parameter | The strategic interaction among countries, non-monetary environmental values | Despite all the model’s limitations and acknowledged uncertainties, the authors claim that the main result is unaffected | It is optimal to undertake both abatement and SAI. SAI reduces abatement costs. SAI worsens climate change governance problems | × |

Note: WITCH, world induced technical change hybrid model.