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Review Article

The Real Economics of Climate Engineering

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In 2008 Scott Barrett wrote a paper on "The incredible economics of geoengineering" in which he argued that the potentially low cost of climate engineering (CE) measures together with the quick response of the earth's temperature to such interventions will change the whole debate about the mitigation of climate change. Whereas Barrett was mostly focusing on the cost of running CE measures, we point out that several determinants of overall economic cost like price or external effects are not yet sufficiently accounted for and that the question of dynamic efficiency is still unresolved. Combining the existing theoretical investigations about the topic from the literature, we show that even though these new measures provide new options to deal with climate change, several of them might also reduce our scope of action. Consequently, we suggest that economic research should shift its focus to portfolios of CE measures and put more emphasis on those measures which control atmospheric carbon concentration and therefore allow extending our scope of action. Additionally, economic research should address the question of phase-in and phase-out scenarios for measures which directly influence the radiation balance.

1. Introduction

The international consensus about limiting the average temperature increase to 2°C was confirmed once again at the recent meeting of the parties to the United Nations Framework Convention (UNFCCC) in Cancun [1]. But greenhouse gas emission (GHG) trends and the corresponding reduction announcements challenge the credibility of this target. Estimates in the World Energy Outlook (2010) show that while it is indeed still possible to meet this target via conventional emission control measures, dramatic emission cuts will be imperative in the near future [2]. A postponement of these emission reductions would involve a drastic increase in mitigation costs and would seriously undermine the probability of staying within the 2°C target. In comparison with a more efficient mitigation course, the fairly moderate emission reductions in the Copenhagen Accord up to 2020 are estimated to involve an additional $US 1 trillion in investment costs in the period from 2010 to 2035 [2]. Expanding the cumulative emission budget for the period 2000 to 2049 from 1000 Gt CO_2 to 1437 Gt CO_2 would be sufficient to increase the maximum probability of exceeding the 2°C target from 42 percent to 70 percent [3]. Furthermore, even today's atmospheric GHG—notably carbon concentrations—cannot be regarded as safe with respect to potential tipping points in the climate system with dramatic climate change as a consequence (e.g., [4, 5]). In the light of this development, it is not surprising that scientists have started discussing alternative technical measures for counteracting climate change. Climate engineering is the blanket term used to refer to such measures.

Climate engineering (CE) is defined as the large-scale manipulation of the earth's radiation balance for the purpose of mitigating anthropogenic climate change (e.g., [6]). The measures can be distinguished according to whether they influence the carbon concentration in the atmosphere (Carbon Dioxide Removal—CDR) or directly affect the earth's radiation balance (Radiation Management—RM).

CDR measures address the root of the problem, but their limited potential means that it will take decades before they have an influence on temperature. On the face of it, a number of RM measures apparently hold out prospects of influencing temperature within a matter of years, but their actual application might lead to a new, artificial climate with various characteristics that are hitherto unknown.

While at first sight CDR measures seem to be very similar to existing emission reduction measures, RM measures definitely provide a distinctive new option in the bid for climate change mitigation. This assessment is bolstered by initial estimates suggesting that the operational costs for these measures would be much lower than conventional emission control, implying that the global problem of climate change could be solved now by a single or small group of countries [7, 8].

Accordingly, two central pillars in the debate about CE are discussed by economists: (1) what would be the optimal level of CE in an optimal climate change reaction portfolio, and (2) how is conventional emission control affected by the use of CE or possibly even mere research into CE? The assessment of these 2 issues is essential for decisions on whether and how the various CE measures might be applied and how their application might affect the future of international climate mitigation negotiations. This paper seeks to outline a framework for the discussion by providing an overview on the current knowledge we have about the feasibility and the costs of the various CE measures. The discussion of potential external effects highlights that economic costs could be considerably higher than existing estimates of operational costs suggest. On the basis of this overview and existing economic studies analyzing the implications of CE, the paper then investigates the insights available on the economic consequences of considering such measures for the climate change reaction portfolio.

Attempts at engineering the climate for the modification of weather variables reach back to the 19th century [9]. As early as 1965, advisors of US President Johnson suggested counteracting the warming of the earth by spreading out reflective particles on the ocean. In the following decades, the debate focused more on the enhancement of natural carbon sinks. While the possibility of enhancing oceanic carbon uptake by iron fertilization has so far only been tested in small-scale field experiments, the possibility of enhancing terrestrial carbon uptake by land-use change and afforestation measures (LULUCF) was written into the Kyoto Protocol. Ideas about directly influencing the radiation balance (e.g., [10–13]) regained a place in the climate change debate through the work of Crutzen in the year 2006. Based on the measurement of the effects of the Pinatubo eruption in 1991, he calculated the amount of sulfur that would need to be injected into the stratosphere to counteract the global warming resulting not only from continuously increasing greenhouse gas emissions but also from the expected loss of cooling due to reduced industrial sulfur emissions.(Crutzen points out that industrial sulphur emissions counteract an ill-defined fraction of global warming from increased greenhouse gas emissions by reflecting solar radiation back into space. However, these sulfur emissions have severe impacts on human health and ecosystems so that political declarations were announced to reduce them. The cooling effect could be approximated by injecting a much smaller amount of sulfur not into the troposphere (like industrial emissions) but into the stratosphere, where the measure could also be extended to compensate for a doubling of atmospheric CO_2 concentration.) Since then, an increasing number of scientific publications have investigated the various options and their side-effects. In 2009, the Royal Society Report published an overview report of this kind that also discusses related political, ethical, and governance issues.

Economic matters related to CE were first addressed by Schelling [7] in a special issue on the topic in *Climatic Change*. He points out that the CE option might turn the climate change problem upside down by reducing the global problem of emission control to a problem where a single state or a small group of states alone can decide on how to counteract climate change. Similar issues are explored by Barrett [8], who concludes that the economics of CE presents a very different set of incentives from mitigation. He argues that CE shifts the challenge from the payment issue that has hitherto been central to the climate change debate to a governance issue. Victor [14] argues that, with respect to governance, we need to create major initial incentives for intensive research into, and assessment of, the various measures with a view to determine which measures qualify for inclusion in a CE portfolio. In his assessment he suggests that, in the event of implementation, CE would probably not be restricted to a single measure but take the form of a portfolio of various CE measures, including compensation mechanisms. Kousky et al. [15] also discuss a portfolio approach, concentrating on the risk of catastrophic climate change and arguing that a well-designed portfolio would comprise mitigation, adaptation, and CE measures.

This overview of the literature sets out to challenge two important aspects that have been taken for granted. One central assumption about CE is that it costs much less than conventional emission control. However, this assumption derives from scientific modeling studies and engineering feasibility studies that do not contain detailed cost estimates. Furthermore, research is advancing so fast that for several measures the cost estimates in the report of the Royal Society [6] are already outdated. Accordingly, the present paper summarizes the available information about the operational costs, discusses factors neglected in these estimates (like price effects), points out that for several measures recent costs estimates are still lacking, and explains why it is important to take a closer look at dynamic efficiency in comparing RM measures with CDR or emission control measures. Second, while a number of important economic issues related to CE have been addressed in the overviews referred to above, others have been largely ignored. A small number of papers have been published that analyze the economic aspects of CE from a theoretical or qualitative perspective in greater detail and with a special emphasis on incentives and strategic interactions. Accordingly, we review these papers and draw conclusions with respect to the impact that the consideration of CE measures might have on the existing climate mitigation efforts and the economic consequences of actual CE implementation.

The paper is structured as follows. Section 2 briefly explains the climate system and the potential CE measures that can influence it. Section 3 presents an overview of the currently available information related to the operational and social cost of various CE measures. Section 4 reviews theoretical studies that analyse the implications of CE for the existing climate policy portfolio. A distinction is made between models which take a central planner's perspective (Section 4.1) and models which investigate the issue from a decentralized perspective (Section 4.2). Section 5 discusses and concludes.

2. Classification of Climate Engineering

For the classification of the various CE measures we consider a simplified representation of the earth's radiation balance based on Feichter and Leisner [16] and Heintzenberg [17]. Short-wave solar irradiation on the atmosphere is determined by the solar constant S_0. About 70 percent of this irradiation is absorbed (51 percent by the earth's surface, 17 percent by aerosols and clouds in the troposphere, and 2 percent by ozone in the stratosphere). Accordingly, about 30 percent is reflected back into space by the atmosphere and the surface of the earth. The relation of reflection to irradiation is called albedo, A. These two variables, S_0 and A, determine the earth's overall short-wave solar radiation energy input, $F_{SW} = S_0(1 - A)$. The irradiation absorbed is converted into latent heat and is returned to space as long-wave thermal radiation. Fraction α of the long-wave thermal radiation is absorbed in the atmosphere mainly by water vapor and other greenhouse gases (GHGs). From there it is emitted back to the earth's surface and out into space. Without this absorption, the average temperature on earth would be -18°C instead of 15°C. On balance, solar irradiation F_{SW} is equivalent to thermal radiation, F_{LW}, the latter being determined by the temperature on the ground and in the atmosphere. From this simplified representation, temperature T at ground level can be expressed as

$$T = \sqrt[4]{\frac{S_0(1 - A)}{2\sigma(2 - \alpha)}}, \tag{1}$$

where σ is the Stefan Boltzmann constant [16]. So far, anthropogenic intervention influences the albedo A and the absorption fraction α. The former is mainly influenced by changes in land use and aerosol emissions, the latter by emissions of GHGs. Change in land use and aerosol emissions lead to an increase of A and hence produce a cooling effect compared to preindustrial levels. Overall, this cooling effect is outweighed by the warming effect from GHG emissions, which represent an increase of α over and against its preindustrial level. The IPCC [18] estimates that in sum the average net anthropogenic effect amounts to about $+1.6(+0.6$ to $+2.4)$ Wm^{-2}. Consequently, since the radiation budget is in a state of imbalance, the temperature of the earth is bound to increase. The reason why the radiative forcing induced so far has not been fully translated into a temperature increase has to do with the inertia of the earth's climate system and in particular the thermal capacity of the ocean (e.g., [19, 20]). The temperature reaction induced by the existing disturbance of the radiation balance is expected to take several more decades before it comes to full fruition [21].

All variables in (1) can be influenced by RM measures. Accordingly, RM can be further distinguished according to whether it influences solar irradiation by changing S_0 or A (Solar Radiation Management) or influences thermal radiation by changing α (Thermal Radiation Management). CDR measures only influence α by affecting the atmospheric carbon concentration. CDR measures can be further distinguished according to whether carbon removal is dominated by biological, chemical, or physical processes. Table 1 gives an overview of the various CE measures and potential realizations.

The classification in Table 1 is not entirely correct because feedback mechanisms mean that RM measures also influence carbon uptake, while changes on the earth's surface mean that CDR measures can also influence the planetary albedo.

3. Operational and Social Cost

We can think of the cost of CE implementation in three ways. The first (and most common one at present) looks at the cost of setting up and running a particular CE measure at current prices for capital goods and material inputs. The second perspective takes account of the fact that large-scale implementation of a certain CE measure will raise demand for certain materials and goods, so that their prices may rise significantly. Substantial expansion of certain industries may even be necessary to meet the demand for products required by a CE measure. Thirdly, the appropriate cost perspective for an analysis of the overall economic effects of a CE implementation involves determining the social cost of the implementation, that is, looking at the operational costs plus the external costs—net, of course, of potential external benefits. At present, knowledge about the price effects and the social cost of CE is more or less non-existent.

Currently available information about the operational costs of CE measures allows only a rough estimate. The published cost estimates are based on modeling studies of the CE measures and engineering feasibility studies, not on empirical tests. New modeling results about the necessary amounts of iron, lime, or sulfur to be spread out on the oceans or injected into the stratosphere will likely change the current cost estimates substantially. For example, the requisite amount of sulfur injected into the stratosphere to offset a warming corresponding to a doubling of atmospheric carbon concentration was estimated in the Royal Society Report [6] to be between 1 and 5 Mt S. More recent estimates suggest that between 9 and 10 Mt S is probably nearer the mark, provided it is spread out as sulfur trioxide or sulfuric acid over anarea of 30°S and 30°N. Otherwise the amount required could be as high as 75 Mt S [23, 24]. Consequently, the estimated operational costs for changing the radiation balance by 1 Wm^{-2} with this CE measure could go up to \$US 67 B (using existing airplanes) [25]. In the Royal Society Report they were estimated just to be about \$US 200 M.

Alongside the imponderables always inherent in theoretical modeling studies, one major uncertainty besetting estimates of operational costs from an economic perspective arises from price effects. Many CE measures require large investments or complicated infrastructures and major material inputs in order to be effective from a global perspective.

Table 1: Classification of various CE measures.

Classification	Effect	Measure	Realization
Radiation management (RM)	Reducing solar irradiation (lower S_0; SRM)	Space measures	Placing mirrors or dust in space
	Increasing albedo (higher A; SRM)	Stratospheric measures	Injection of sulfur or nanoparticles
		Cloud measures	Injection of salt aerosols into marine stratus clouds
		Surface measures	Modification of crop, forest, desert, or urban albedo
	Increasing F_{LW} radiation (lower α; TRM)	Cloud measures	Injection of bismuth(III) iodide into cirrus clouds
Carbon dioxide removal (CDR)	Reducing F_{LW}-absorbing atmospheric carbon (lower α)	Biological-based measures	Biochar production, afforestation, ocean iron fertilization
		Chemical-based measures	Spreading pulverized lime or calcium hydroxide in the ocean, air capture
		Physical-based measures	Enhancing downwelling currents

Source: [16, 17, 22].

So they may have a strong impact on those markets representing the sources of such goods and materials. In the cost studies we have, these effects have been neglected. For example, measures like spreading out lime on the ocean would require a huge number of ships, which in its turn would lead to a substantial demand shift on the global ship market. Similar, albeit smaller in scale, effects can be expected for the global airplane market if measures like sulfur injection into the stratosphere were to be realized on a large scale. Price effects may also occur on the supply side due to CE implementation. Afforestation may increase the supply of wood once the trees mature; carbon capture may lead to the creation of CO_2 certificates changing the market price of carbon. These effects may also lead to a change in relative prices in the world economy.

Scientific studies on the different CE measures have shown that their use may have unintentional side-effects, referred to in economics as “external effects.” It is essential to take these potential side-effects into account and include them in the analysis of the social cost of CE. They can take the form of external costs or external benefits. Side-effects can be related to the material in use or the spreading mechanism. They could also materialize as impacts on certain ecosystems or overall changes in the climate system. For example, CDR measures intended to increase oceanic carbon uptake by stimulating algal growth would affect by definition the oceanic ecosystems and could have on the one hand negative consequences for certain species and overall biodiversity (e.g., [26, 27]). On the other hand there might be positive impacts for certain fish stocks [27] or even for the endangered whale population [28]. Global side-effects may arise in the climate system if the greenhouse gas-induced change in the absorption of thermal radiation is compensated for by changing, say, the reflection of solar irradiation. The reason is that the greenhouse gas-induced radiative forcing is more or less equal across regions, whereas the negative radiative forcing of RM measures is strongest at places with high irradiation. Consequently, using RM measures to compensate for GHG-induced radiative forcing can be expected to result in effects that differ from region to region (e.g., [29]). This regionally uneven change implies that other climate variables will also react to RM in a regionally differentiated way. For example, RM measures may successfully reduce the global temperature, but as a side-effect they may also lower precipitation in some regions of the world [16, 30]. However, these effects are not well understood yet, and current simulation models disagree on the impacts for various regions (e.g., [29, 31–33]). Given these uncertainties about the reaction of the earth system at both the local and the global level, it is not surprising that there are almost no assessment studies that attempt to place an economic value on regional side-effects and in particular the side-effects related to the reaction of the climate system to RM implementation. One exception is the study of Pongratz et al. [34], who analyze the impact of RM implementation on crop yield. They show that even though RM implementation could reduce precipitation, the associated decrease in temperature does also reduce evapotranspiration so that the overall effect on moisture might not necessarily be negative. Additionally, they show that due to the still prevailing CO_2 fertilization effect, crop yield could increase, at least compared to the situation without RM intervention in a high-CO_2 world. Moreover, crop yield could also be positively influenced by the increase in diffuse irradiation over and against direct irradiation as a result of stratospheric sulfur injection [35]. These examples not only show the uncertainty about the side-effects but also the uncertainty about their consequences for economic costs. Irrespective of these uncertainties, any large-scale intervention into the earth ecosystems or the climate system will result in distributional implications because some regions will gain and some regions will lose. However, such distributional implications will also occur as the consequence of unmitigated climate change. Whether CE implementations could smooth or would further aggravate such distributional implications is still unresolved.

Tables 2 and 3 give an overview of the published estimates for the operational costs of CDR measures and RM measures, respectively, including information on their potential, the expected investment requirements, and the major uncertainties related to these estimates. The tables also indicate the side-effects that may arise, both positive and negative. However, these tables are based on existing publications and contain therefore for some measures out of date estimations as there are no new findings available. Consequently, the tables provide rather a snapshot on existing estimates than a conclusive cost overview.

Table 2 does not include physical-based carbon dioxide removal measures because the currently proposed methods are either not covered by our definition of climate engineering (carbon injection into the deep ocean) or cannot be considered effective CDR measures (enhancing downwelling currents) ([84] and [85], resp.). Also excluded are continental afforestation and oceanic macronutrient fertilization measures, the latter could be realized either by nutrient supply from land via pipelines or from the deep ocean via artificially enhanced upwelling. These biological carbon removal measures are omitted from the discussion because they are either inefficient or ineffective [50, 86, 87]. Table 3 does not show measures for modifications in space designed to change solar irradiation. Such measures, for example, placing mirrors in the earth's orbit, are highly inefficient and exceed the Royal Society estimate based on conventional measures by a factor of between 8 and 9 [25]. Nor does the table feature surface measures addressing the albedo of urban areas (e.g., roofs and streets) and deserts because these measures are either ineffective on a global scale or inefficient. The table does not include surface measures addressing the albedo of the ocean, like ship-based generation of microbubbles in the ocean [88], because there are yet no reliable cost estimates available. The measure for the modification of marine stratus clouds refers only to Flettner ships. Technically speaking, the modification could also be performed by airplanes, but there are no studies available on such an approach.

The cost estimates in Table 2 show that the operational costs of the CDR measures are within the range of the costs that have been projected for conventional emission control for the year 2035, for example, by the IEA [2]. However, such a comparison is not entirely above criticism, one reason being that it significantly underestimates the total cost of CDR. Various CDR measures, like spreading pulverized calcium hydroxide or pulverized lime, are expected to require large investments in installations and logistic infrastructures, and the associated capital costs are frequently omitted from the estimates of the operational costs in Table 2. In addition, the operational cost of a CDR measure refers to the outlays for input, labor, and capital, whereas the marginal abatement cost of emission control is defined as the amount of social product (GDP) lost if the emissions of a ton of CO_2 are avoided. Accordingly, emission control costs take into account the processes of adjustment with which an economy responds to the increasing demand for resources and the accompanying price effects. Those processes are ignored in the operational cost computations for CE measures. Another economic source of expenditure left out of account both in the operational cost of CDR and in the abatement cost of emissions is associated with the external effects of CDR and emission control, respectively. The external costs of CDR tend to be negative, thus prompting underestimation of the overall economic cost. However, technological progress and the scale effects possibly occurring in conjunction with the large-scale implementation of CDR measures can contribute to a lower estimate of their cost.

The cost estimates in Table 3 show that in particular marine stratus and potentially cirrus cloud modification seem to be relatively cheap in terms of operational costs. This assessment has to be taken with caution because these estimations are not just out of date but seem to be done with a lack of thoroughness. This becomes, for example, obvious by looking at the estimates for R&D costs related to the development of Flettner ships where common sense tells us that the actual costs will be way above $US 27 M. Furthermore, bearing in mind the cost development of stratospheric sulfur injection since the publication of the Royal Society report referred to earlier, it seems more than likely that the estimated costs for these measures will also increase accordingly. The estimated costs for sulfur injection into the stratosphere seem to be more reliable and would even be affordable for a rich country or a small group of rich countries if the injection would be done with existing airplanes. However, all measures that seem to be capable of reducing the radiative forcing associated with a doubling of atmospheric CO_2 concentration to preindustrial levels potentially involve large external effects on the climate system. As we have said, these effects are not yet well understood, but they certainly have the potential to incur social costs and distributional implications. As it is the case for CDR measures, technological progress and scale effects can contribute to a lower estimate of the cost of RM measures.

The comparison between RM and CDR measures is anything but straightforward given that RM potential is usually measured in Wm^{-2} whereas CDR potential is measured in carbon units (C), for example, gigatons (Gt) C or atmospheric carbon concentration units (ppm). Neither of these units of measurement is readily convertable, since the influence of atmospheric carbon concentration on the radiation balance is nonlinear. An increasing atmospheric carbon concentration implies that also increasing amounts of carbon have to be removed to observe the same change in the radiation balance. (Given the atmospheric carbon concentration is 450 ppm, the necessary amount of carbon to be removed for a change of 1 Wm^{-2} in the radiation balance is estimated to be about 178 Gt C; given that the atmospheric carbon concentration is 750 ppm, this amount increases to about 297 Gt C). Consequently, comparison between these two measures must take the prevailing atmospheric carbon concentration into account. In economic terms, we could say that the higher the atmospheric carbon concentration is, the less costly RM measures become relative to CDR measures as a way of changing the radiation balance. However, the higher the atmospheric carbon concentration already is, the longer RM measures have to be maintained until natural processes have reduced the atmospheric carbon concentration to a level where the RM measure can be discontinued. Accordingly,

Table 2: Overview of current operational cost estimates and potential side effects for various CDR measures.

Measure	Potential	Operational costs in US/tCO_2	Main investment requirements	Uncertainties	Side-effects	Sources
Biological-based carbon dioxide removal						
Biochar production	5 Gt CO_2/year	45 (15–76)	Bio-char production units	Net carbon storage potential due to use as energy source; use as fertilizer may reduce costs	Use as fertilizer increases net primary production; residuals from pyrolysis process might limit application for food production	[36–44]
Southern Ocean iron fertilization	5 Gt CO_2/year	45 (8–82)	Iron sulfate production and treatment, ship fleet for spreading (20–500 ships)	Necessary amount of iron sulfate; coagulation of iron sulfate; increase in export production; leakage (even though accounted for in the estimate for potential)	Impacts on marine biogeochemistry, ecology, and biodiversity; increases nutrient supply for fish stocks, change in oxygen minimum zones, temporary acceleration of oceanic pH value (faster acidification)	[26–28, 45–51]
Afforestation	4 Gt CO_2/year	60 (19–101)		Measurement of carbon uptake and leakage varies between studies; unintended carbon release due to fire, storms; impact on albedo	Ecological effects and implication for biodiversity; land requirements	[6, 52–54]
Chemical-based carbon dioxide removal						
Spreading pulverized olivine	4 Gt CO_2/year	42 (27–57)	Exploitation, transport, pulverization, and spreading infrastructure	Access to target area (tropical catchment areas of large rivers) for spreading	Increase in soil and oceanic pH value (reduced ocean acidification); ecological impacts (e.g. input of silicic acid into oceans)	[55–57]
Spreading pulverized calcium hydroxide	1.5 Gt CO_2/Gt $CaCO_3$	50 (45–54)	Exploitation, transport, thermal treatment, storage for separated CO_2, fleet for spreading (about 3000 ships)	Exploitation and spreading logistics, uptake limited due to ocean circulation, storage of separated CO_2	CCS-related side-effects; increase in oceanic pH value (reduced ocean acidification)	[58–60]
Spreading pulverized lime	0.3 Gt CO_2/Gt $CaCO_3$	65 (57–72)	Exploitation, transport, pulverization infrastructure, fleet for spreading (between 4000 and 6000 ships)	Exploitation and spreading logistics, uptake limited due to ocean circulation	Increase in oceanic pH value (reduced ocean acidification)	[59]
Air capture (sodium hydroxide)	1.0–1.2 Mt CO_2/unit/year	250 (69–430)	$US 247–480 M/unit	Storage of captured carbon, energy provision	Carbon-Capture-and-Storage-(CCS-) related side-effects	[61–66]
Comparison to existing abatement measures						
Conventional emission control for limitation to 2°C increase by 2050	21 Gt CO_2 (in 2035)	90–120 (in 2035)	$US 940 B/year (2020–2035) $US 1280 B/year (2030–2035)	Simulation results	Side-effects associated with nuclear power, CCS, and biofuel production	[2]

Detailed derivation of estimates can be found in [25].

Table 3: Overview of current operational cost estimates and potential side-effects for various RM measures.

Measure	Annual potential in Wm^{-2}	Operational costs in B \$US/Wm^{-2}	Main investment requirements	Uncertainties	Side-effects	Sources
SRM surface measures						
Modification of crop and forest albedo	−1	No quantitative assessment available, but operational costs and investment requirements are expected to be relatively low		Genetic modifications; replacement of existing plants	Increases effectiveness of afforestation; side-effects due to genetic modifications	[6, 67]
SRM cloud measures						
Modification of marine stratus clouds by injection of salt aerosols from Flettner ships	−4	0.135	R&D \$US 27 M; Setting-up \$US 30 M; ship fleet \$US 1.7 B; additional logistic and maintenance costs (e.g., ports)	Automatic operation of ships; replacement and maintenance requirements; Flettner rotors	Salt is nontoxic and residence time is low (<2 weeks); climatic side-effects	[32, 33, 68, 69]
TRM cloud measures						
Modification of cirrus clouds by injection of bismuth(III) iodid	−1 to −4	No quantitative assessment available. Spreading is suggested to be done from airplanes on scheduled flights, implying cost in the order of magnitude or even lower as for modification of marine stratus clouds; otherwise, cost estimates from sulfur injection can be applied; understanding of cloud dynamics is low and in turn necessary spreading amounts are highly uncertain			Bismuth(III) iodide is nontoxic and residence time is low (<2 weeks); climatic side-effects	[70–72]
SRM stratospheric measures						
Sulfur injection; existing airplanes (>18 km)	Unlimited	16–67	Airplane fleet \$US 18–56 B; base station \$US 1 B per unit	Coagulation between already existing and newly injected particles and therefore spreading amount; estimation of fuel costs; sulfur logistics; existing airships would only allow spreading height of 6 km	Recovery of ozone layer slows down; increase of anthropogenic sulfur emissions by 10 to 17 percent; ratio of diffuse irradiation to direct irradiation increases resulting in higher net primary production and lower solar power generation; perception of sky changes (less blue skies, more red sunsets); space observation affected; climatic side-effects	[23, 24, 29, 31, 35, 73–83]
Sulfur injection; newly designed airplanes (>18 km)	Unlimited	2–12	Airplane fleet \$US 6–36 B; base station \$US 1 B per unit			
Sulfur injection; newly designed airships (>18 km)	Unlimited	5–18	Airship fleet \$US 19–66 B; base station \$US1 B per unit			

Table 3: Continued.

Measure	Annual potential in Wm^{-2}	Operational costs in B \$US/Wm^{-2}	Main investment requirements	Uncertainties	Side-effects	Sources
Injection of engineered nanoparticles	Unlimited	No quantitative assessment available; prototypes do not exist; irrespective of construction costs, spreading amount is estimated to be 0.1 Mt implying cost reductions up to the order of 200 in comparison to sulfur injection			Residence time of nanoparticles; climatic side-effects	[81]
			Comparison to existing abatement measures			
Conventional emission control (450 to 550 ppm CO_2 by 2100)	−2 to −5	200	\$US 940 B/year (2020–2035) \$US 1280 B/year (2030–2035)	Time period for comparison; based on annual share of GDP (0.5 to 1 percent); simulation results	Side-effects associated with nuclear power, CCS, and biofuel production	[2, 6]

Detailed derivation of estimates can be found in [25].

RM measures become more expensive in terms of accumulated costs. Consequently, comparison between the cost of CDR and of RM measures depends not only on the reference atmospheric carbon concentration but also crucially on the reference period chosen.

The Royal Society [6] bases its comparison on the period up to year 2100. The assumptions are that an unmitigated scenario will result in an atmospheric carbon concentration of 750 ppm in the year 2100, while in an emission control scenario the concentration will be stabilized at 450 to 550 ppm. The accumulated cost of this emission control scenario is translated into cost per Wm^{-2} per year and is then compared to the cost of RM measures per Wm^{-2} per year. This approach ignores the fact that in 2100 emission control would result in a comparatively low CO_2 concentration. By contrast, if the same temperature had been achieved via RM, the atmospheric concentration would still be about 750 ppm. As a consequence, the RM measures would have to be maintained until the concentration had declined by natural processes to levels that are not considered harmful. Consequently, the comparison of costs presented in the Royal Society [6] overestimates the costs of conventional emission control, since it does not include the follow-up cost of maintaining RM measures for temperature control. A truly appropriate cost comparison would have to be based on a dynamic analysis in which the cost of achieving the effect on temperature obtained by the mitigation of a given emission—say one Gt CO_2—is compared to the cost of achieving this same temperature effect by means of an RM measure. To the best of our knowledge, a dynamic cost comparison of this kind has yet to be attempted, but it would be highly desirable for comparisons between RM, CDR, and emission control measures.

4. Economic Models of Climate Engineering

As we saw in the previous section, the information about operational costs available at present only allows for a very limited comparison with existing mitigation measures. Economic adjustment processes to a large-scale implementation of CE measures are not included in these estimates. Furthermore, no reliable cost estimates exist for the external effects. Accordingly, economic analyses on climate engineering have so far been restricted to analytical approaches deriving general implications of CE from theoretical models and (illustrative) quantitative results based on highly aggregated simulation models like DICE. The existing literature focuses on RM measures because those measures provide a distinct new option for the climate change reaction portfolio. Research approaches can be divided into those that investigate CE from a central planner's perspective and those that adopt a decentralized perspective.

4.1. Centralized Climate Engineering Decisions. We begin by discussing the research that investigates the globally optimal application of CE in a static framework. In such a framework there do not appear to be many new insights to be gained from analysing CDR measures, as their economic impact would only differ from existing emission control with respect to cost. However, including both RM and CDR measures would allow for factoring in feedback mechanisms like the positive effect of a temperature decrease caused by the application of RM on carbon uptake by biologically based CDR measures.

Moreno-Cruz and Smulders [89] consider these feedback mechanisms to some extent, although they only consider RM measures and conventional emission control. In their theoretical model, the sum of mitigation costs and global damage costs are minimized in a static framework, while mitigation costs are determined by the application of conventional emission control and RM measures. Social costs are determined by atmospheric carbon concentration, temperature increase, and side-effects of RM. The influence of the atmospheric carbon concentration on social costs is nonmonotonic because the authors consider both external benefits with respect to a CO_2-induced increase in plant productivity and external costs with respect to CO_2-induced ocean acidification. The temperature is determined by the atmospheric CO_2 concentration and the application of RM measures, while temperature in its turn also affects natural CO_2 uptake. (Beside the positive effect of temperature reduction while the CO_2-fertilization-effect is still present [34], it would also be legitimate to consider the positive effect on carbon uptake deriving from the increase in diffuse irradiation over and against direct irradiation as a result of stratospheric sulfur injection [35].) This would also allow to investigate possible complementarities between RM and CDR measures, however, the authors restrict the analysis to RM measures and emission control. The influence of temperature and side-effects of RM on social costs is monotonic and convex, as is the influence of emission control and RM measures on mitigation costs.

The results of the model are straightforward. Given that it is possible to increase welfare by the application of RM, RM is used in such a way that marginal costs are equal to marginal benefits and conventional mitigation measures are to some extent substituted for by RM. The substitution effect depends on the curvature of cost functions for both measures. Additionally, the substitution effect is limited by the influence of CO_2 concentration on social costs because once a certain concentration threshold has been exceeded these costs increase in CO_2 concentration and which cannot be compensated for by RM measures. One rather theoretical result that Moreno-Cruz and Smulders [89] come up with is that the application of RM does not necessarily imply a higher atmospheric carbon concentration but may even produce a lower concentration compared to the situation where only mitigation measures are in use. This result depends on the magnitude of the substitution and the feedback effect on natural carbon uptake. The authors show that it is possible to construct a situation where zero or even negative values for the optimal carbon emission tax occur. In this theoretically specified case, the effect of increased carbon concentration on the global temperature is controlled via RM measures. At the same time, the benefits of an increased fertilization effect are so high that the carbon concentration resulting from unmitigated carbon emissions would be too low.

The crucial assumption for the results in the paper by Moreno-Cruz and Smulders [89] is that the application of RM makes it possible to increase global welfare, or, to put more explicitly, that the social benefits induced by the reduction of temperature will outweigh the social costs accruing from the side-effects.

This central assumption is further investigated by Moreno-Cruz et al. [90]. They determine the optimal level of RM with respect to external effects in the climate system by drawing on the findings of the study by Ricke et al. [29], who use the general circulation model HadCM3L to investigate the regional change in temperature and precipitation caused by a doubling of CO_2 concentration with and without RM compensation. While on a global average the application of RM does indeed make it possible to compensate for a greenhouse gas-induced temperature increase, the extent of this compensation will vary regionally. Moreover, other climate variables like precipitation or polar ice coverage may be either too large or too small compared with the original situation. To account for these effects, the authors use a residual vector model that measures the deviation in temperature and precipitation from the situation without climate change. As mentioned, the application of RM does not make it possible to reverse both variables to the situation without climate change. The residual vector model measures aggregated squared residuals of these two variables on an annual basis for various regions on the earth. The variables are normalized and measured in standard deviations obtained from the situation without climate change to account for regional variability. The authors determine the global optimal level of RM by minimizing the regional aggregated deviations weighted either by population, economic output, or land area.

With this model Moreno-Cruz et al. are able to show that while such a globally optimal level leads to a high degree of compensation for both temperature and precipitation, there are also regions where the deviation is larger than it would be with unmitigated climate change. These regions would suffer a reduction in welfare from the globally optimal policy. Therefore, instead of looking for a globally optimal RM level, the authors suggest going in search of finding a Pareto-improving RM level. The Pareto-improving level is determined by increasing the RM level until an additional amount of RM would start to make a region worse off again with respect to the aggregated squared deviation in temperature and precipitation.

The authors argue that a Pareto-improving RM level would be possible, implying that every region or country would have an incentive to accept such an RM level. In their analysis, the region determining the Pareto-improving RM level is Western Africa, with an RM level that is 78 percent of the global optimum. However, it should be noted that the Pareto-improving RM level is based on the deviation in physical units and not on a monetized and regionalized impact assessment. In addition, precipitation and temperature change are equally weighted, even though some regions might be more seriously affected by temperature, others by precipitation, and others again by the change in the variability of these variables. Finally, the analysis does not consider "climate change winners" because it measures the deviation from the situation without climate change without taking account of the fact that various regions stand to gain from climate change. In fact, from the "climate change winners" perspective, it seems doubtful whether a Pareto-improving RM level actually exists. Nevertheless, to our knowledge this paper is the first to address regional variation in side-effects and highlights the fact that the optimal level of RM is not necessarily the one that fully offsets greenhouse gas-induced temperature increase. Nevertheless, the results are preconditioned by the assumption that RM intervention makes it possible to increase social welfare. With respect to the potential side-effects, this can be considered a crucial assumption that needs to be further investigated.

Adopting a dynamic perspective makes it possible to analyze one distinctive feature of RM measures: their reaction advantage over existing mitigation options in the presence of unforeseen climate change dynamics. It also enables us to investigate the implications of controlling for the increase in global temperature while doing nothing to address the root of the problem. Moreno-Cruz and Keith [91] analyze these features by considering two different decision-making stages with a time interval between them. In the first stage, uncertainty exists about the climate sensitivity which is then revealed in the second stage. In the first stage, the optimal level of emission control is determined, and once climate sensitivity is known, the optimal level of RM is chosen based on this new information. The social costs are determined by the CO_2 concentration, the side-effects of RM, and the temperature increase, the influence of the three variables being additive-separable, monotonic, and convex. Consequently, in contrast to Moreno-Cruz and Smulders [89], positive CO_2 fertilization effects are not considered. The temperature response to an increase in atmospheric carbon concentration is determined by climate sensitivity. The mitigation costs are convex, while the costs of RM are linear, implying that the level of RM is determined by its effectiveness in decreasing temperature and its side-effects. The mitigation costs and social costs due to increased temperature are calibrated with Nordhaus' DICE model [92], while the social costs due to the increase in CO_2 concentration are calibrated based on the analysis by Brander et al. [93]. With respect to the effectiveness of RM in decreasing temperature and the influence of its side-effects on social costs, various scenarios are considered. The authors show that the higher the effectiveness of RM and the lower the impact of the side-effects of RM, the lower the mitigation effort at the first stage. However, the authors also show that even in the case of low effectiveness and high side-effect impact, RM will be used to some extent at the second stage if climate sensitivity turns out to be substantially high due to the convexity of the optimization problem.

The intertemporal substitution effect illustrates the insurance character of RM measures. If there is a measure that is conducive to response if climate change turns out to be worse than expected, it will be optimal to choose a lower level of precaution. Moreno-Cruz and Keith [91] also analyze the case where the benefit of an RM measure is in itself uncertain with respect to effectiveness in lowering temperature. As expected, this results in higher mitigation efforts at the first stage compared to the case with complete knowledge about effectiveness. The authors argue that in a situation like this emission control and RM measures become risk complements.

These implications of CE and particularly RM are confirmed and extended in the articles by Gramstad and Tjötta [94] and Goes et al. [95]. Both apply the DICE model taken from Nordhaus [92] and consider four scenarios: (1) business as usual (BAU), (2) optimal emission control, (3) optimal emission control and RM implementation, and (4) optimal implementation of RM only. Both articles show that the third scenario (emission control plus RM) is optimal with respect to social welfare and confirm the substitution effect between emission control and mitigation in this scenario. Gramstad and Tjötta also indirectly confirm the reaction advantage of RM by showing that in the optimal scenario (3) there are only minor welfare losses associated with postponing RM implementation for 20 or 30 years.

However, with respect to the insurance character of RM, Goes et al. [95] show that welfare losses in the fourth scenario exceed even those in the BAU scenario (compared to the optimal scenario) if the implementation of RM is interrupted. Though this result is based on a modified function for the social costs by placing additional weight on the rate of temperature change, it shows that the insurance character of RM might be lost owing to the possibility of interruption, which would imply possible rapid climate change (e.g., [96–98]). Nevertheless, it should be noted that the results are derived from the scenario with only RM implementation to counteract climate change. As pointed out by Bickel and Agrawal [99] assuming that the implementation of RM is still accompanied with some level of emission control, or at least a sufficient increase in emission control is possible once RM implementation is truncated, increases the number of scenarios with RM implementation which pass cost-benefit tests.

There are almost no analyses addressing aspects of CDR measures in a dynamic context. One of the rare exemptions is Rickels and Lontzek [100], who consider the possibility of increasing oceanic carbon uptake, but again in an isolated manner without the simultaneous consideration of RM measures. Their analysis follows in the footsteps of Marchetti [101], who suggested injecting carbon directly into the ocean.(Marchetti [101] was the first author to use the term geoengineering in the context of climate change mitigation.) This measure may not be climate engineering in the strict sense of the term, as the measure would require capturing industrial CO_2 emissions and does not remove carbon from the atmosphere. But Rickels and Lontzek analyze this measure in a rather stylized way so that the results also apply to oceanic CDR measures like iron fertilization or chemical enhancement of alkalinity. The authors show that also the application of CDR measures results in a substitution of conventional emission control which in turn allows extending the period in which fossil fuels can be extracted in reasonable amounts. Despite this substitution effect on emission control, the overall effect on atmospheric carbon concentration is positive because the atmospheric carbon peak concentration is lower along its optimal path compared to the situation without CDR utilization. This has important implications for the more climate policy relevant case where an exogenous ceiling is defined for atmospheric carbon concentration. Such a ceiling could, for example, correspond to the 2°C limit for temperature increase as is now widely accepted by many countries. Rickels [102] shows that the utilization of CDR measures like increasing oceanic carbon uptake allows that the ceiling is reached later in time than without utilization of such measures. Taking into account the difficulties in determining a ceiling on atmospheric carbon concentration that can be regarded as safe with respect to climate change, it is obvious that CDR measures increase our scope of action, in particular when new findings indicate that a lower ceiling is necessary to comply with the temperature limit.

However, long-term effects have to be taken into account in analyzing CDR measures. Rickels and Lontzek [100] show that the long-term atmospheric carbon stabilization level might increase due to the fact that the ocean could become supersaturated with anthropogenic carbon resulting in carbon leaking back into the atmosphere in the long-run. This issue raises the question how to deal with CDR measures that involve temporary storage characteristics. The assessment of temporary versus permanent storage requires a positive value for time. The Kyoto Protocol defines the period of 100 years as basis for the assessment of permanence [103], implying a discontinuous value of time. This decision was not based on scientific rationale but on a political will [104].

Not just to this respect, discussion of the pros and cons of CE measures calls for an assessment of their potential impacts on climate change and potential side-effects that reaches well into the future. For such an assessment, the determination of appropriate social discount rates is crucial. This topic goes beyond the scope of this paper, and we refer to, for example, Dasgupta [105] and Heal [106] for recent overviews of the aspects to be considered.

4.2. Decentralized Climate Engineering Decisions. In analyses of centralized climate engineering decisions, one crucial assumption is that the application of CE—and in particular RM measures—will actually bring about an improvement of global welfare. However, this assumption still needs to be empirically validated. If this is not the case, the question arises as to whether a small number of countries might choose to use RM measures without international consent because it is very likely that the assumption will be fulfilled for single regions or countries. Such a uni- or minilateral implementation seems to be feasible for a number of measures if one considers the implementation costs and their effectiveness in controlling temperature [7, 8, 107]. Consequently, the scientific community has a particular interest in papers that investigate the use of RM from a perspective where several actors may decide independently on implementation. The different actors do not necessarily need to represent different countries. They could also represent different generations.

In a static framework, this issue is addressed in the second part of the article by Moreno-Cruz and Smulders [89].

Again, social costs are determined by the CO_2 concentration, temperature increase, and side-effects caused by RM, as set out in the previous section. The authors consider n actors, for example, countries, where one actor can unilaterally implement RM. The remaining $n-1$ actors can only determine their level of emission control. Each of the $n-1$ countries minimizes its own social costs (the cost of emission control plus social costs), taking into account the emission control measures opted for by the other actors and the level of RM chosen by the one actor. The unilateral actor minimizes global social costs by selecting the level of RM, taking the emission control opted for by the $n-1$ actors as given.

In such a situation, the substitution effect between emission control and RM measures is influenced by the free-rider problem. From a global perspective, countries would choose a lower level of emission control than is optimal even without the unilateral RM implementation. The possibility of using RM amplifies the free-rider effect, resulting in even lower emission control plus higher RM implementation than is globally optimal.

To our knowledge, there are no other analyses discussing the implications of RM implementation from a decentralized perspective, which is surprising. In particular, the static analysis by Moreno-Cruz et al. [90] referred to in the previous chapter would be an interesting starting point for a decentralized optimization perspective, with respect not only to the optimal level of RM but also to new incentives with a bearing on climate change negotiations. Rickels et al. [108] discuss the latter point with reference to CDR. They analyse the implications of integrating carbon credits from large-scale iron fertilization into a static compliance problem for the year 2020. Besides analyzing the market requirements (prices, amount of carbon credits) for iron fertilization to compete with emission control and afforestation, they also investigate the distributional impacts.

As expected, their results indicate that "carbon credit selling countries" (most of them developing countries) experience a reduction in profits whereas "carbon credit buying countries" are more or less indifferent between extending carbon credit supply from Clean Development Mechanism (CDM) projects and opting for carbon credit supply from iron fertilization instead. The authors argue that it might be possible to design a new option in which allocation of carbon credits from iron fertilization is conditional on accepting emission reduction targets. This would create new incentives for developing countries to join a global climate regime, while developed countries are more or less indifferent. Overall, the new option would require more ambitious emission reduction targets to ensure carbon price stability.

Such new incentives for mitigation of climate change by CDR measures might require modifications to the negotiation framework for international climate treaties. This question is addressed in an intertemporal framework by Barrett [109], who analyzes possible international treaties about the level of emission control and of air capture. He assumes the cost of emission control to be convex and that of air capture to be linear and relatively high. Furthermore, he assumes that applying air capture does not in itself imply social damages due to side-effects. Barrett posits a three-stage decision game. In stage one, countries decide on whether to participate in an international treaty, in stage two those participating decide on their level of emission control and/or air capture, while in stage three nonparticipants decide on their level of emission control/air capture. He argues that separate treaties for emission control and air capture are not cost-efficient due to the difference in marginal costs for the measures, while due to the relatively high constant marginal costs of air capture, a combined treaty based on cost-effectiveness might not be self-enforcing. Consequently, if new measures like air capture are integrated into international treaties, the preference for cost-effectiveness would need to be reassessed. Cost-effectiveness in second-best treaty arrangements might imply that air capture would not be used, even though its usage would increase welfare. Barrett argues that, in such a situation, separate treaties covering the different measures may be superior to cost-effectiveness.

Analyses of globally optimal CE measures have identified a fundamental substitution effect between emission control and CE. This may no longer be true if consideration extends to a large number of actors valuing the use of CE differently. This eventuality is investigated by Moreno-Cruz [110]. He uses the basic model setup by Moreno-Cruz and Keith [91], but transfers it to a two-country decision problem where countries are differently affected by climate change and the side-effects of RM. In the two-stage decision problem, both countries decide simultaneously about emission control in the first stage and about RM implementation in the second stage. In the second stage, the social costs related to climate change and the side-effects of RM are known; that is, there is no uncertainty about climate sensitivity. Again, countries minimize social costs resulting from the expense of emission control/RM implementation plus economic damages. First, the author considers the case where both countries are similar in their perception of climate-change- and RM-related social damages. Once more, the outcome confirms the technical substitution effect between emission control and RM implementation, resulting in lower aggregate emission control in the first stage. In contrast to Moreno-Cruz and Keith [91], this result is based on cost-effectiveness only and not on the reaction advantage of RM implementation with respect to uncertain climate sensitivity. Alongside the substitution effect, the two-country decision problem is also affected by the free-riding factor. Both countries anticipate that a lower level of emission control will result in a higher level of RM in the second stage and have an incentive to realize lower emission control in the first stage. However, the author argues that because the two countries are very similar, the influence on emission control is dominated by the substitution effect and not by the strategic effect.

Turning to a more interesting case, the author assumes that the countries are differently affected by climate change and RM-related side-effects. He demonstrates that a situation may arise in which one country does not implement RM measures in the second stage because it is strongly affected by these side-effects. Despite this, the other country will still implement RM measures conditional on the aggregate emission level observed in stage one. Accordingly, the country strongly affected by RM-related side-effects has an incentive to increase its emission control in the first stage so that the other country will choose a lower level of RM in the second stage. The author points out that this effect might result in a situation where aggregate emission controls exceed that in a situation where the option of RM implementation is not available. Such a situation could arise if one country is assumed to be "climate change winner" and the other country a "climate change loser." The former would have little incentive for emission control. However, if it is also an "RM loser" it will have an incentive to increase emission control, taking into account that the "climate change loser," has a strong incentive to choose a high level of RM. However, the result of increasing overall emission control due to unilateral RM implementation requires rather strong assumptions which are probably not fulfilled in reality. First of all, the state or region representing the "RM loser" would have to be sufficiently large so that its increased emission control would have an effect on global climate change. Furthermore, in such a case as pointed out by, for example, Horton [111], it is more likely that the affected state or region would apply counter RM measures to offset the negative impacts.

It should be noted that the results in Moreno-Cruz [110] do not necessarily require the countries to be differently affected by RM-related side-effects in physical or economic terms. It would be sufficient for them to value RM-related side-effects differently, due, say, to ethical considerations. This idea is taken up in the analysis by Goeschl et al. [112], where the authors consider two generations which do not overlap. Effectively, they also use a two-stage decision problem in which uncertainty about climate sensitivity exists. It is assumed that climate sensitivity and hence the related climate change-induced social costs are either high or low. The uncertainty about climate sensitivity is revealed in the second stage, and the economic damages are also only realized in stage two. The first generation decides on its level of emission control and whether or not it intends to invest in R&D for the development of RM measures. This latter decision determines the availability of the option of implementing RM measures in the second stage. Consequently, the second generation decides about whether it will implement RM measures or not, provided the necessary R&D has been done in the first stage. RM implementation also causes side-effect-related social costs. The first generation behaves altruistically, minimizing the sum of social costs over both stages which are determined by emission control, R&D investment, climate change, and the RM-related side-effects, where climate change and RM-related side-effects if implemented are only realized in stage two. The costs for emission control are assumed to be convex, the R&D investment costs for the development of RM measures to be a fixed amount, and the cost of RM implementation in stage two to be zero. The social costs caused by RM-related side-effects are assumed to be linear and the social costs caused by climate change to be convex, implying convex benefits for RM implementation.

However, the distinctive feature of the model proposed by Goeschl et al. [112] is that the social costs due RM-related side-effects are assessed differently between generations and that the first generation takes into account this possibility in its altruistic optimization decision. In the reference case without different assessment, the first generation invests in R&D, and the second generation implements RM measures if climate sensitivity turns out to be high. Again the substitution effect is observed, implying a lower level of emission control in the first stage than would have been chosen without the option of implementing RM measures. The authors then analyze the case where the second generation's assessment of the RM-related side-effects is lower than that of the current generation. Consequently, the second generation might also have an incentive to implement RM measures if climate sensitivity turns out to be low, even though this was not intended by the first generation. As a result, the first generation deviates from optimal behavior in the reference case. Three strategic options are available for the first generation: (1) increasing emission control and investing in R&D so that the second generation has lower incentives for implementing RM measures; (2) increasing emission control but refraining from R&D investment so that the second generation cannot implement RM measures; (3) decreasing emission control and investing in R&D, accepting that RM measures will be implemented at stage two. The strategic option realized depends on the choice of parameters.

The authors also consider the case where the second generation assesses the RM-related side-effects to be very large. Consequently, the second generation might have an incentive to refrain from implementing RM measures, even if climate sensitivity turns out to be high. Again, the first generation changes its behavior, having two potential options: (1) increasing emissions control and saving the investment for R&D and (2) reducing emission control substantially and investing in R&D so that the second generation is "forced" to implement RM measures. Both cases show that, in general, different assessments of RM or CE might alter the substitution effect observed in the analyses discussed in the previous section. Furthermore, the authors emphasize that the current generation cannot take an isolated decision about CE research without considering the potential options for its application.

5. Discussion and Conclusion

Since the pioneering articles by Schelling [7] and Barrett [8] on the economic prospects of climate engineering, economic research has made progress in this sector and has started to analyze several aspects of this new option for climate mitigation in more detail. Even though economic research is still restricted to analytical approaches and (illustrative) quantitative results, this development has provided not only new insights on how a climate mitigation strategy might change due to these new options, but has also revealed that there are still large gaps in our knowledge.

In particular, current knowledge about the economic costs of the various CDR and RM measures is unsatisfactory. First, for several measures there exist no recent or reliable estimates with regard to operational costs (running and capital costs). For example, the estimates for the modification of stratus and cirrus clouds are far too low compared with sulfur injection in the stratosphere or other comparable projects for modifications at via ships or airplanes. Second, for almost all measures, the capital costs have not been adequately considered as part of the operational costs. The rare exceptions are (to some extent, at least) the estimates for stratospheric sulfur injection and the setting-up of air-capture installations. For other measures, like spreading pulverized calcium hydroxide or pulverized lime, huge capital investments would be necessary for large amounts of carbon to be removed from the atmosphere, resulting in substantial capital costs for such measures. Third, the estimates do not account for price effects. Large-scale implementation of certain measures is expected to raise the prices of the inputs accordingly so that operational costs would also increase. Fourth, the estimates have so far been restricted to operational costs and do not include social costs or benefits due to external effects. By definition, any large-scale intervention in ecosystems and/or the climate would not only affect one variable but also would change the ecosystems and create a new artificial climate. Accordingly, external effects would occur, and it is still unclear to what extent social costs or benefits would be associated with these effects. Irrespective of whether additional costs or benefits arise, these effects would not be equally distributed over the world, and some regions might gain, while others might lose. Fifth, the existing estimates do not adequately address dynamic issues. Even though the annual costs for certain RM measures might be considerably lower than those for emission control or CDR measures, the accumulated costs for RM measures could be higher over time because causative measures like emission control and CDR need to be applied once with respect to one unit of carbon in the atmosphere, whereas symptomatic RM measures have to be maintained until the unit of carbon has been removed by natural processes.

Further research should address these issues to create more reliable knowledge about the costs of the various measures. Updating of cost estimates and adequate consideration of capital costs and price effects can be expected to increase the costs for several measures significantly. Nevertheless, due to the high leverage of certain RM measures in affecting the temperature, these measures are expected to remain cheaper by a factor of 10 to 100 than emission control or CDR measures, if the comparison is restricted to annual operational costs. This appraisal might change if comparison were extended to accumulated social costs. Due to the continued limitations of our knowledge about regional variation in the extent of temperature control and the potential for reduced precipitation, the uncertainty about the social costs of RM measures may possibly stay as it is, unless such measures are tested or applied on a large scale. However, a dynamic cost comparison of emission control or CDR measure with RM measures (including feedback mechanisms) is feasible with existing scientific models and would be highly desirable from our point of view. Furthermore, existing cost estimates for the various measures have been investigated in a rather piecemeal way. As pointed out by Victor [14], the application of CE measures will probably take place in the form of a portfolio comprising various measures. Consequently, feedback and interaction effects have to be investigated further. For example, the effectiveness of afforestation measures could be raised if they were combined with genetic leaf modifications, as this would not only remove carbon but also improve the albedo of forest areas. Also, measures that may seem ineffective on a global scale (e.g., increasing the albedo in urban areas) might support emission control on a local scale via energy efficiency gains and temperature decrease.

Regarding the question of how emission control policies might be affected by the new option of CE, the economic analyses that have been done so far should be regarded as initial theoretical explorations in a field where empirical assessments are still almost completely absent. But they provide important new insights and indicate many directions for further research, especially with regard to the sometimes different views on the impact of CE which are given in the political sciences. So far, the analyses have focused on RM measures because on the face of it these represent a distinctive new option with respect to their effectiveness in influencing the radiation balance because they come with ostensibly low operational costs, and not least because they may fundamentally change the climate change reaction portfolio.

In particular, Schelling [7] emphasizes the potential of RM measures to resolve the dilemma of the need for global cooperation on emission control measures. RM measures would enable a single state or small group of states to effectively cool down the earth. This is an interesting aspect of RM measures, but it needs to be further investigated with respect to several strategic interaction effects which have not been considered by Schelling. For instance, the analysis by Moreno-Cruz [110] shows that the planned implementation of RM measures could in theory lead to even more overall emission control because so to speak "RM losers" would have an incentive to increase their emission control activities in order to reduce the incentives for the implementation of RM measures. However, as we have already pointed out, such a result requires rather strong assumptions; in particular the "RM losers" have to be sufficiently large for their increased emission control to have a significant effect on global climate change. In reality, it seems more likely that (1) unilateral RM implementation would amplify the free-riding problem, as several states would choose an even lower level of emission and rely on the unilateral RM actor [89], and (2) potential "RM losers" would apply counter-RM measures to offset the negative impacts [111].

In particular, the work of Horton [111] shows that in reality it is rather unlikely that RM measures are implemented unilaterally because such unilateral activities are constrained by the international logic of multilateralism. He also points out that while multilateralism does not necessarily imply global cooperation, it does imply mechanisms for achieving consensus. Such mechanisms would also have to deal with compensation schemes for negative side-effects that some regions are likely to experience. With respect to compensation schemes the analysis by Moreno-Cruz et al. [90] suggests that even if it were possible to define an "optimal" level of RM in terms of global temperature and precipitation adjustment, it seems unlikely that all countries would agree to such a level because the regional manifestation of these climate variables would vary considerably and would therefore have very different welfare effects at the regional level. Their conclusion that a kind of Pareto-improving RM level exists and could be accepted by all countries seems unlikely, given the fact that it is very likely that some countries are expected to benefit from climate change. Therefore, an important avenue for further research would be the exploration of potential compensation schemes for RM measures.

We believe that the novelty of RM measures in the climate change reaction portfolio arises in particular from their reaction advantage. Due to the high leverage of certain measures to change the earth's temperature, there would be practically no alternative to those measures if it became necessary to reduce temperatures quickly. Such a necessity could arise if climate sensitivity turns out to be higher than expected, or if the climate system becomes likely to cross certain tipping point. The analysis by Moreno-Cruz and Keith [91] shows that even in the case of low effectiveness and high side-effects of RM, it will be used to some extent if climate sensitivity turns out to be substantial. However, their analysis also shows that if there is a measure that provides fast fixes if climate change turns out to be worse than expected, it will be optimal to choose a lower level of precaution in terms of emission control. Consequently, the substitution of emission control by RM measures follows not only from the potential cost advantages of RM measures but also from their insurance character against unforeseen climate change. The latter mechanism implies that research into RM measures with the aim of achieving operational readiness for those measures will be enough to result in a lower level of precaution in terms of emission control [112]. Consequently, RM measures might induce new dilemmas for climate change mitigation because research into such measures itself already increases the probability that these measures will actually be applied because emission control has been significantly reduced (e.g., [25]).

One such potential dilemma from the increased likelihood for the implementation of RM measures could be the materialization of a lock-in effect. Since RM measures are designed to manipulate the global climate system, unforeseen side-effects might result from such an intervention, potentially some years after implementation. The analysis by Goes et al. [95] suggests that in such a situation it might be difficult to truncate RM implementation. As RM measures mitigate climate change symptomatically and not causatively, truncation would result in rapid climate change with probably high social costs. These costs are likely to exceed the costs associated with the unintended side-effects of RM measures which were mentioned above. Therefore, societies may be locked into a situation where they are forced to continue RM even thoughs—looked at the decision from an ex-post perspective—they would never have chosen to introduce RM measures.

The analysis by Brovkin et al. [97] shows that RM measures have to be maintained for several thousand years unless they are accompanied by sufficiently strong emission control measures that eventually make RM measures unnecessary. In their analysis, the authors consider the application of various levels of RM to reduce the temperature increase associated with a cumulative emission of 5000 Gt C, where 90 percent of this amount is emitted in the period between 2000 and 2300. (Though this amount seems to be rather high in absolute terms, it implies lower carbon emissions in the period from 2000 to 2100 than the IPCC's SRES A2 Scenario. It also represents a rather conservative estimate of the earth's fossil fuel resources. The analyses by Sinn [113] and Edenhofer and Kalkuhl [114] show that there is good reason to believe that a large fraction of these resources will be used.) Their emission scenario results in a peak temperature increase by 7°C in 2350. The authors show that the implementation of RM reduces the global temperature and results in lower concentration of CO_2 than in a scenario without RM implementation. However, they point out that the compensating effect of RM would need to be maintained for several thousand years because even in year 10000, 40 to 60 percent of the carbon emitted would still be in the atmosphere.

Obviously, RM measures should be accompanied by a sufficiently high level of emission control or by CDR measures to such an extent that they reduce the risk of the above mentioned lock-in effects. As argued by Moreno-Cruz and Keith [91], it follows from the reaction advantage of RM measures on the one hand and potential uncertainties related to their effectiveness and their side-effects on the other hand that the control of emissions and RM should be seen as complementary risk-control factors. Even though the results produced by Goes et al. [95] provide an important foundation for the discussion of the termination issue of RM measures, their results have been criticized. The analysis by Bickel and Agrawal [99] points out that Goes et al. proceed on the basis of some rather strict assumptions because they do not consider potential adjustments in the degree of emission control measures in the situation when RM measures are terminated. By assuming that the application of RM is accompanied by at least some degree of emission control or at least that a sufficient increase in emission control is possible once RM application is truncated, Bickel and Agrawal [99] show that this increases the number of scenarios where the use of RM measures passes cost-benefit tests. Accordingly, their analysis provides an important starting point for further research investigating possible phase-in and phase-out scenarios. Phase-in scenarios could provide valuable information for potential RM field tests, as they would show the social costs resulting from terminating RM after different periods of implementation. Phase-out scenarios could provide valuable information as to what level of emission control and/or CDR implementation would be necessary to allow for a smooth phase-out of RM measures.

All in all, it appears that CE-related economic research tends almost to neglect CDR measures. One possible explanation for this is that CDR measures are more similar to emission control. Both constitute a causative approach to the mitigation of climate change, but they are too limited in their effectiveness to quickly reduce global temperature. However, CDR measures have a strategic efficiency advantage over emission control [25]. Emission control reduces the demand for fossil fuels, causing their global market price to fall. Consequently, if only some countries introduce emission control, the lower global market price will mean that nonparticipating countries will use more fossil fuels and their emissions will increase accordingly (e.g., [113, 115–117]). This effect is defined as international carbon leakage and is an indicator for the relationship between the rise in emissions by nonparticipating countries and the reduction in emissions by participating countries [118]. Another problem associated with mitigation instruments solely focusing on the demand side of fossil fuels is that strategic behavior of fossil fuel owners is not accounted for. Consequently, the introduction of instruments for controlling emissions could result in a situation where fossil fuel consumption would simply be moved forward in time but not avoided entirely [113, 114]. CDR implementation is a way of circumventing these effects, because it does not directly influence the demand for fossil fuels. Consequently, in contrast to emission control, it is also effective if applied at a nonglobal level. These insights have not yet been explicitly explored with reference to CDR, but they can be extrapolated from research on carbon capture and storage (CCS). Quirion et al. [119] show that in a scenario restricting emission control to OECD countries, international carbon leakage can be more than halved if CCS is combined with emission control.

Furthermore, CDR implementation also provides new incentives for global emission control negotiations. These incentives arise from the fact that CDR implementation could generate carbon credits that are tradable on an international carbon market. The carbon credits might either originate from CDR projects on the territory of countries that could then directly be used for trading or originate from CDR projects on international territory like the oceans, which would then have to be allocated to the countries according to some allocation scheme specifically used for trading. In the latter case, Rickels et al. [108] argue that it might be possible to design a scheme in which allocation of carbon credits from international CDR implementation is conditional on the acceptance of emission reduction targets. This would create new incentives for developing countries to join a global climate regime, while developed countries remain more or less indifferent. Overall, the inclusion of carbon credits from CDR implementation would require more ambitious emission reduction targets to ensure carbon price stability and would therefore not only provide incentives for developing countries to join a global emission trading scheme but also increase the overall effect on atmospheric carbon concentration.

Without adjusting the emission targets in such a scenario, the carbon price would fall thus resulting in reduced conventional emission control. This shows that in general CDR measures will to a certain extent be a substitute for conventional emission control. Unlike the situation with RM measures, the atmospheric carbon concentration would decrease. In theory, this result is also possible for RM measures, provided that the positive temperature feedback effect on natural carbon uptake overcompensates the substitution of emission control [89]. However, this result is based on rather strong assumptions connected with the feedback effect and unlikely to materialize in reality. Consequently, CDR measures make it possible to reach a lower atmospheric peak concentration and to move towards potentially critical thresholds for atmospheric carbon concentration levels at a later point in time [100, 102]. Given the uncertainties in defining safe levels of atmospheric carbon concentration in terms of the corresponding degree of climate change, it is obvious that CDR measures will increase our scope of action, in particular when new findings indicate that lower levels are necessary to comply with a certain limit for the increase in temperature above the preindustrial levels.

CDR measures could hence increase our scope for action, whereas RM measures or even research related to these measures could result in a lower level of precaution in terms of emission control and therefore an ultimate reduction of our scope for action. Accordingly, one might argue that climate policy research should focus more on CDR measures. This is especially the case if the economic analysis starts to focus more on the dynamic efficiency of RM measures, not just with respect to its reaction advantage, but also with respect to its potential for long-term implementation and the problems associated with a possible necessary phase-out. Given the results obtained by Gramstad and Tjötta [94], who show that welfare losses caused by postponing RM implementation by 20 to 30 years would be rather modest, a priority for CDR research would appear to be reasonable. Furthermore, defining the implementation readiness of certain CDR measures as a precondition for research on RM measures could be an option to deal with the negative strategic side-effects resulting from the expectation of the operational readiness of RM measures in the future. In order to deal with the problems resulting from RM research leading to operational readiness of the measures, one could also restrict RM research to improving the understanding of the earth system and the evaluation of the side-effects that might result from RM measures. In this respect, the study by Pongratz et al. [34] serves as a good starting point for future research.

Nevertheless, as pointed out by Barrett [107], restricting research on CE or RM or even on certain measures would be reckless in view of a potentially disastrous and sudden climate change. The study by Solomon et al. [120] shows that the current carbon concentration could be already sufficient to trigger irreversible damage through sea-level rise or changes in precipitation patterns. Consequently, postponing research on RM measures may not be in line with a precautionary approach to control the negative effects of climate change. Furthermore, as argued by Victor [14], any ban or taboo on certain CE measures or CE in general would probably lead to the exploration of these measures by less responsible and scrupulous governments and individuals. These considerations and the overview about the theoretical economic insights show the complexity of the whole CE debate. Our paper is intended to make proposals for further research on this topic, but we need to keep in mind that decisions related to climate engineering should not only be based on scientific or economic arguments but also require an interdisciplinary approach encompassing political, social, legal, and ethical perspectives.

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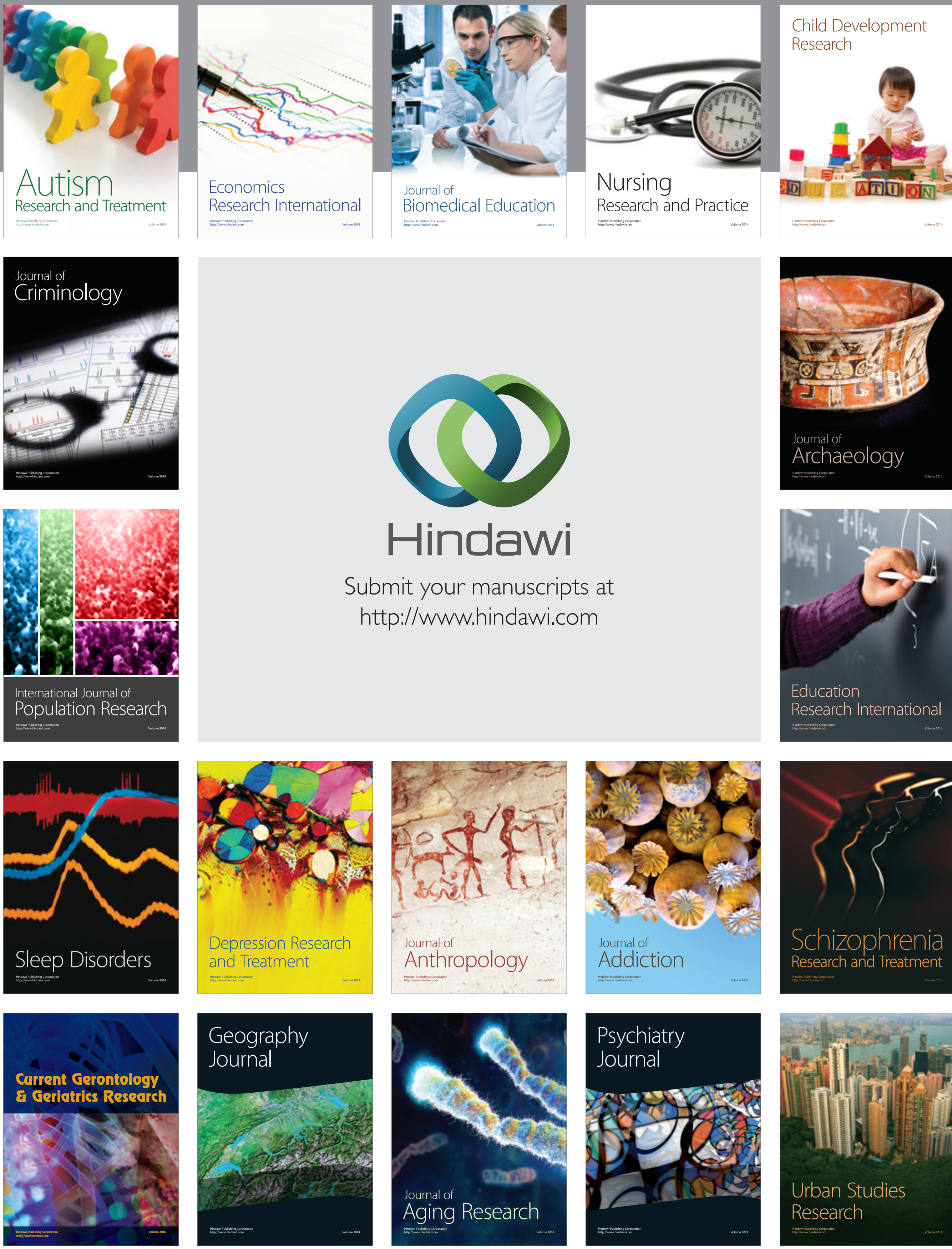
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