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Challenges and Opportunities for Integrated Modeling of Climate Engineering

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Summary

The Paris Agreement has set stringent temperature targets to limit global warming to 2°C above preindustrial level, with efforts to stay well below 2°C. At the same time, its bottom-up approach with voluntary national contributions makes the implementation of these ambitious targets particularly challenging. Climate engineering – both through carbon dioxide removal (CDR) and solar radiation management (SRM) – is currently discussed to potentially complement mitigation and adaptation. Results from integrated assessment models already suggest a significant role for some forms of climate engineering in achieving stringent climate objectives1. However, these estimates and their underlying assumptions are uncertain and currently heavily debated2–4. By reviewing the existing literature and reporting the views of experts, we identify research gaps and priorities for improving the integrated assessment of climate engineering. Results point to differentiated roles of CDR and SRM as complementary strategies to the traditional ones, as well as diverse challenges for an adequate representation in integrated assessment models. We identify potential synergies for model development which can help better represent mitigation and adaptation challenges, as well as climate engineering.

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JEL Classification: Q5, Q55

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Challenges and opportunities for integrated modeling of climate engineering

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The Paris Agreement has set stringent temperature targets to limit global warming to 2°C above preindustrial level, with efforts to stay well below 2°C. At the same time, its bottom-up approach with voluntary national contributions makes the implementation of these ambitious targets particularly challenging. Climate engineering – both through carbon dioxide removal (CDR) and solar radiation management (SRM) – is currently discussed to potentially complement mitigation and adaptation. Results from integrated assessment models already suggest a significant role for some forms of climate engineering in achieving stringent climate objectives[1]. However, these estimates and their underlying assumptions are uncertain and currently heavily debated[2–4]. By reviewing the existing literature and reporting the views of experts, we identify research gaps and priorities for improving the integrated assessment of climate engineering. Results point to differentiated roles of CDR and SRM as complementary strategies to the traditional ones, as well as diverse challenges for an adequate representation in integrated assessment models. We identify potential synergies for model development which can help better represent mitigation and adaptation challenges, as well as climate engineering.

Motivation

The Paris Agreement has provided new impetus to the complicated negotiation process of international climate policy. Two elements of the treaty are important for the scope of this paper. Firstly, the agreement has emphasized the importance of keeping long-term temperature increase well below 2°C compared to pre-industrial, aiming even for a 1.5°C target. Keeping temperature increase below 2°C or 1.5°C (with likely chances) will require not exceeding cumulative emissions budgets, calculated from the year 2017 onward, of 750 and less than 100 GtCO2, respectively (see https://www.mcc-berlin.net/en/research/co2-budget.html, based on existing sources [1 5]). An IPCC special report will be devoted to analyzing the impacts and the climate change strategies needed to achieve the most stringent target. Secondly, the agreement is built around a bottom-up, hybrid architecture with a focus on short term national mitigation pledges. Top-down coordination is limited to the periodic revision and evaluation of the proposed contributions, with the possibility to "ratchet up" at national level again.

These two elements originate from disparate angles and may conflict with each other. On the one hand, the focus on very low temperature targets originates, at least partly, from the current impacts of climate change that are found to be more severe than previously estimated[6]. Already with 1.5°C warming, impacts are projected to be unacceptably high for vulnerable nations. Recent research has shown that climate change can have severely negative and persistent impacts on, among others, economic growth, public health, and social conflicts[7–10]. Additional impacts, such as those on ecosystems, have not yet been comprehensively quantified. Non-linear feedbacks and tipping points in the climate system provide additional motivations for strict control over long term as well as short term temperature changes[11,12]. The fragmented outcome of the Paris agreement is, on the other hand, the result of a lack of institutional mechanisms for enforcing global climate cooperation. As it is clear from the recent change in the US national climate politics, voluntary commitments can be uncertain and inherently fragile.

The rapid depletion of the remaining carbon quota, and the unresolved difficulty of moving from political reality towards globally coordinated climate policy, inevitably requires a serious consideration of climate engineering. Climate engineering comes in two fundamentally different forms. CO_2 removal (CDR, also known as negative emissions) aims at increasing or mimicking the Earth's natural carbon sequestration mechanisms, which act via a variety of physical, chemical, and biological pathways to remove carbon from the atmosphere. CDR does not directly change the climate. However, it has been traditionally categorized as a climate engineering strategy to distinguish it from standard emission reduction measure because it deliberately manipulates aspects of the Earth System. CDR options include biological sequestration such as afforestation, bio-char and bioenergy with carbon capture and storage (BECCS), ocean iron fertilization and chemical absorption such as direct air capture (DAC), enhanced weathering or ocean alkalinity management [13–15]. Extrapolating current annual emissions (2016 emissions from fossil fuels and industry are estimated to be 36.4 $GtCO_2$) the 1.5° budget will be exhausted before the year 2020. By removing CO_2 (including that coming from non-point sources and that emitted in the past) CDR can allow expanding the allowable budget, though it will not allow for decreasing temperatures in the medium-term due to inertias in the carbon-climate system. Indeed, scenarios generated by IAMs show significant overshoot of radiative forcing and temperature for 2°C and especially 1.5°C scenarios (see Figure 1). The amount of overshoot is correlated with how much CDR is expected to be deployed, as indicated by the correlation with BECCS in the same figure.

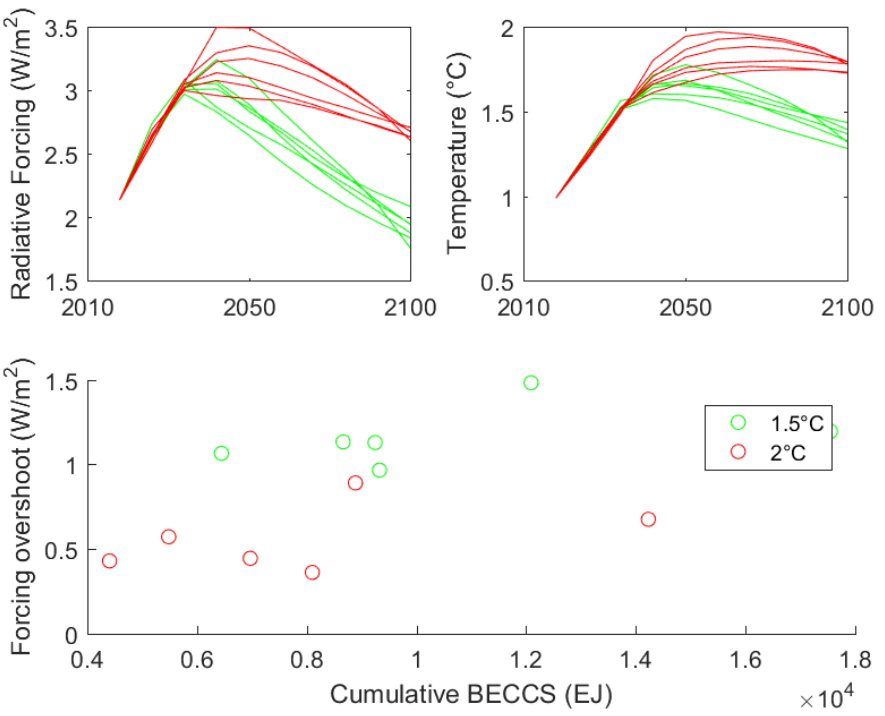


Figure 1: Overshoot in 1.5°C and 2°C scenarios. Top panels: pathways of total radiative forcing and global temperature increase in 2.6W/m^2 (red) and 1.9 W/m^2 (green) end of century stabilization scenarios. These two targets are consistent with 2°C and 1.5°C respectively. Bottom panel: cumulative (2010-2100) production of biomass energy with CCS against overshoot of radiative forcing (max over 2010-2100 minus level in 2100). Each line-dot is a scenario generated by one of the models which implemented the SSPs (AIM-CGE, GCAM, IMAGE, MESSAGE-GLOBIOM, REMIND-MAGPIE, WITCH-GLOBIOM). All scenarios have SSP2-SPA2 socio-economic policy assumptions. Data sources: For 2°C scenarios, Riahi. et. al[16]. For 1.5°C, Rogelj. Et. Al[17].

In contrast to the causative approach of CDR, solar radiation management (SRM), or albedo modification, offers a symptomatic approach by influencing the amount of incoming solar radiation absorbed by the Earth's surface. Options include modification of surface and cloud reflectivity, injection of stratospheric aerosols, and space based methods[13]. As such, SRM can provide almost immediate reduction in regional and global temperature levels. Accordingly, SRM is considered to be used as an additional lever to keep temperature in check and avoid short to medium term damages, as a substitute for some degree of mitigation[18], as a "stopgap" measure to allow time for mitigation[19], or to prevent tipping points[20]. Indeed, the scenarios in Figure 1 show that even with strong mitigation and CDR temperatures will keep increasing at least till mid-century.

Given the different mechanisms they act upon, and the different risks and benefits they entail, CDR and SRM should be seen as distinct climate strategies, as now agreed in the scientific community (see here). However, for the sake of the integrated assessment of different climate strategies –mitigation, adaptation, climate engineering- it is important to look at them together rather than in isolation to allow defining a comprehensive policy portfolio. In the remaining of the paper we will discuss them jointly, though we will emphasize their different nature.

Current status of research on the integrated assessment of CDR and SRM

With the exception of some CDR options -such as afforestation and BECCS, for which practical experience exists- most of the current assessments of climate engineering have been confined to modeling and theoretical assessments. Given the limited knowledge about the costs and the benefits of CDR and SRM, and their possible use for attaining the discussed climate targets, more research should be devoted to increasing the robustness of the current estimates. Important aspects of CDR and SRM have been discussed and assessed in the past few years by a rapidly expanding literature based on model simulations. Our interest is predominantly in the policy evaluations carried out by Integrated assessment models (IAMs). IAMs are numerical models which integrate the climate and human components. Several categories of IAMs exist, depending on the level of resolution and integration of the different sectors - such as the economy, climate, energy, land use and water. IAMs can also serve very different purposes: for example, some models have been used for calculating the social costs of CO2 and evaluate cost benefit tradeoffs, whereas others have mostly focused on evaluating cost effective ways to achieve given policy targets such as temperature targets. The latter class of models has contributed to the IPCC fifth assessment report with more than 1000 scenarios. The representation of CDR and SRM options in IAMs is however very different.

Many IAMs feature CDR technologies among their climate strategies, especially the process based models which have a sufficient detail in the energy sector. For example, all the IAMs which have generated the Shared Socio Economic Pathways (SSPs) scenarios include biological CO2 removal options, such as afforestation and/or BECCS. Already in the IPCC 5th assessment report, almost all the submitted scenarios featured CDR. Indeed, one of the most robust findings coming from model based comparison exercises produced over the past years is that CDR is a fundamental strategy for achieving stringent targets such as 2°C.[1,21] Attaining 2°C requires removal of CO2 from the atmosphere in the hundreds to thousands $GtCO_2$.[2] Scenarios exploring tighter temperature targets such as 1.5°C suggest an even larger role for CDR[5,17]. Depending on technology, CDR can have adverse consequences on competition for land, ecosystems, energy and water[22,23]. Several IAMs include land use and water modules, and have quantified the impacts of biological CDR on food prices, and land use implications[24,25]. Little is known about the timing and potential of the rate of penetration of CDR options, and most importantly, their social costs can only be estimated with high uncertainty. The effectiveness of terrestrial CDR might also be reduced by compensating mechanisms such as CO_2 outgassing from the oceans and hysteresis[26,27].

On the other hand, SRM has been predominantly assessed by small-scale models such as DICE[28–31], with few exceptions[32]. Modeling SRM technologies is not particularly complicated, in terms of costs and effectiveness[33] of controlling global temperatures. However, the reason for the rather stylized investigation of SRM so far rests on very large uncertainties associated with SRM measures. Although investment costs and effectiveness in compensating temperature appear to be well understood, little is currently known about the full costs of SRM, which include direct impacts on socio-economic sectors and its interference with the climate system. The existing model based assessments of SRM have relied on assumptions which allow exploring limiting cases[30]. Moreover, SRM raises unique governance issues due to low investment costs and global impacts, allowing for unilateral implementation by individual countries[34–36]. In addition, SRM only addresses the warming symptoms of rising emissions and does not cure the cause. Therefore, other effects of rising CO_2 concentrations, such as ocean acidification[37], will remain. Depending on how these issues are accounted for, existing studies suggest that either SRM could be an effective complement to mitigation and CDR or not[38].

The policy request to explore low temperature scenarios calls for a robust evaluation of climate engineering options. Despite the different knowledge gaps regarding CDR and SRM and the development stage of their implementation in IAMs, it is difficult to provide confidence statements about the role of CDR and SRM. It is thus important to identify which aspects of climate engineering are most likely to matter for their assessment, and how research gaps can be filled. Some recent contributions have moved in this direction[39,40]. In what follows, we report the outcomes of two complementary approaches to formulate an actionable research agenda for integrated assessment modeling for the upcoming IPCC reports.

Expert views on CDR and SRM potential and research gaps

The limited knowledge about the future prospects of climate engineering needs to be reconciled with the significant role some of these options play in current scenarios produced by IAMs when evaluating stringent climate targets. To this end, we have conducted a survey eliciting the opinions of experts in the field. The main goal of the survey was to better understand the prospects of CDR and SRM respectively, in terms of potential, research gaps and challenges/requirements to model these technologies in the larger context of integrated assessment models. The full text of the survey is reported in the SOM. An online survey was circulated among participants attending two scientific conferences held in the fall of 2016 on the topic of climate engineering and modeling, which brought together researchers in the fields of earth system, economics, and technology modeling of both CDR and SRM. This list was expanded to include the authors of highly cited papers (>80 citations) on CDR and SRM. Overall, we received 30 responses of experts in climate and environmental science, climate policy, integrated assessment modeling, climate economics – mostly from research institutions. See the SOM for additional details.

In the first part of the survey, we asked participants to provide us with their opinion about the future role of CDR and SRM vis à vis mitigation in a series of different climate policy scenarios. We focused on four scenarios meant to span uncertainties about the long term temperature goals (3°C, 2°C and 1.5°C) and the policy architecture to achieve them ('Bottom up' and 'Top Down'). Box 1 in the Appendix provides a description of the policy scenarios as given to respondents.

We highlighted two cases of international policy integration: a 'bottom up' (BU) architecture based on national, voluntary contributions with no coordination or harmonization; and a 'top down' (TD) architecture characterized by global cooperation. These cases represent the status of international climate negotiations and an idealized normative case, respectively. Both are routinely evaluated in model based assessments such as those reported within the IPCC reports. As a counterfactual scenario, against which these policy scenarios are considered, we prescribe a "Business - As - Usual" scenario yielding end of the century radiative forcing between 6 and 8.5 W/m^2 and temperature increase between 4 and 5°C, in line with projections from the IPCC AR5 WGIII (figures 6.6 and 6.13).

The results of the first set of questions are presented in Figure 2, where for each of the three policy tools (Mitigation, CDR, and SRM) we report the elicited relative contribution (in % terms) to achieving the temperature targets prescribed by the four policy scenarios. The ranking of climate strategies provided by the experts is unambiguous. Mitigation is deemed to be the most important climate strategy across the four policy scenarios (mean values: 69%, 57%, 58%, 46%), followed by CDR (14%, 22%, 22% and 28%) and then SRM (3%,8%,7%,13%). The relative weight of climate engineering options increases in the stringency of the climate target. International cooperation (moving from 2°BU to 2°TD) appears to decrease the role of SRM, but not that of mitigation or CDR. Nonetheless, a significant fraction of experts think SRM will play no role whatsoever, though this fraction drops for the 1.5°C scenario (72%, 48%, 52% and 28% for the 4 policy cases). We also asked experts to quantify uncertainties, see Figure S1 in the SOM. Uncertainties about the respective contributions are, as expected, significantly higher for CDR and SRM than for mitigation. Overall, mitigation appears to be a necessary but not sufficient condition for climate stabilization: climate engineering is also needed.

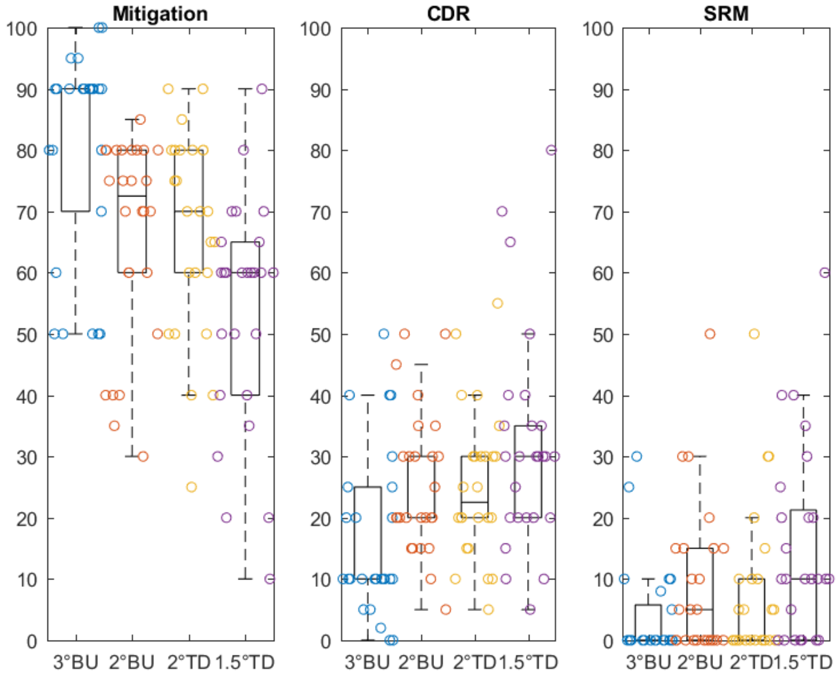


Figure 2: Relative contribution of mitigation (left), CDR (middle), and SRM (right) under four policy scenarios. Each circle is an expert estimate, boxplots provide descriptive statistics (the central mark indicates the median, the edges of the box indicate the 25th and 75th percentiles, whiskers extend to 1.5 interquartile ranges, which represent 99% confidence intervals for normal distribution).

A second key question regards the timing of deployment of these technological strategies, a typical output of IAMs. Figure S2 in the SOM shows experts' views about initial significant deployment (defined as 10% of maximum use) of CDR and SRM. For CDR, there is a clear consensus that deployment should begin soon, especially in low carbon stabilization scenarios. The majority of experts foresee a role of CDR starting before mid-century, across policy cases. SRM shows a significantly different and scattered pattern, with overall later deployment and less clear policy ranking. The exception, once again, is the 1.5°C scenario, where the majority of experts foresee significant SRM deployment even by mid-century.

So far, results referred to global figures, but there could be important regional differences in the timing and potential for deployment of CDR and SRM technologies. These also matter for IAMs, who generally split the world in a set of regions. We consider 8 major world regions: EU, USA, Other OECD countries, China, India, Brazil, energy exporting countries, and other developing countries. For each region, the experts' opinion on the likelihood of deploying each technology in a generic scenario are shown in Figure 3. The chart indicates expert consensus for the regional distribution of CDR, which is seen likely in many countries, especially EU, Brazil, and energy exporting countries. On the contrary, a regional divide emerges for SRM. US, China, India and energy exporting countries are seen as more likely areas for SRM deployment, differently from that of the EU, other OECD and other developing countries. Experts' judgment suggest that SRM could potentially generate regional frictions both among industrialized and developing countries, highlighting the divergence of regional incentives and posing possible challenges to its governance.

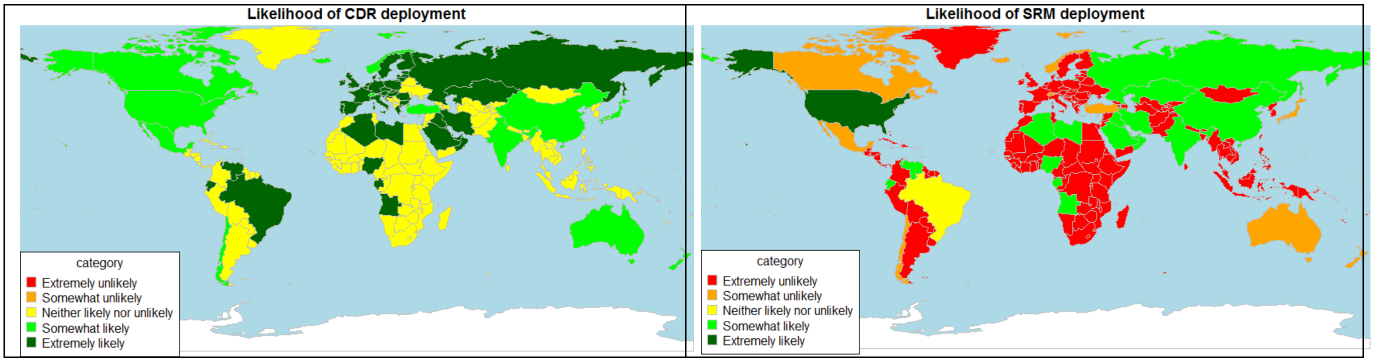


Figure 3: Likelihood of CDR (left), and SRM (right) deployment for different regions (calculated as majority voting of respondents). The red color shows the regions with the least likelihood and the dark green shows the most likely regions to deploy these technologies.

The second part of the elicitation was focused on identifying the research gaps and barriers for either CDR or SRM and for specific technologies within each class of climate engineering. First, experts were asked to allocate a given budget on research priorities and to identify the major obstacles in bringing technologies to market. In order to understand the relative importance of the climate engineering methods and the areas which require more attention in terms of spending research and development and demonstration (RD&D), we asked the experts how they would allocate the hypothetical climate engineering budget among RD&D activities (distinguishing between research, on one side, and development and demonstration, on the other) in CDR and SRM methods (see Figure S3 in the SOM). On average experts allocated 70% of the budget to CDR and 30% to SRM (this may also reflect different expectations regarding the cost of each technology type innovation). The allocation between research versus development and demonstration differs significantly across technologies: for CDR experts foresee roughly an equal split, whereas for SRM research would receive 75% the budget. This reflects the different technological readiness of CDR and SRM, as understood by the expert panel.

For modeling and policy purposes, it is important to understand how different technological solutions for both CDR and SRM will play out, given the heterogeneity of technology options. Experts were asked to allocate the RD&D budget among different CDR and SRM technologies. We considered six CDR technologies (Bio-energy and CCS (BECCS), Bio-char, Afforestation, Direct air capture (DAC), Enhanced weathering, and Ocean fertilization) and four SRM technologies (Surface albedo, Cloud albedo, Stratospheric aerosols, and Space based methods). The results are shown in Figure 4.

Respondents allocate on average about 30% of the total CDR RD&D budget to both BECCS and DAC. The rest of the budget is allocated to Afforestation (average of 14%), Biochar (11%) and Enhanced weathering (11%). The smallest portion of the budget (3%) is allocated to Ocean fertilization (it is important to notice that none of the experts reported this technology as their primary areas of expertise, see the SOM). With few exceptions, IAMs have represented CDR mostly of biological nature (e.g. BECCS and afforestation). These results suggest DAC as an important additional technological option to be considered. For SRM, Stratospheric aerosols receive more than 45% of the R&D budget, followed by Cloud albedo (29%) and Surface albedo (19%) while the smallest portion is allocated to Space based methods (6%).

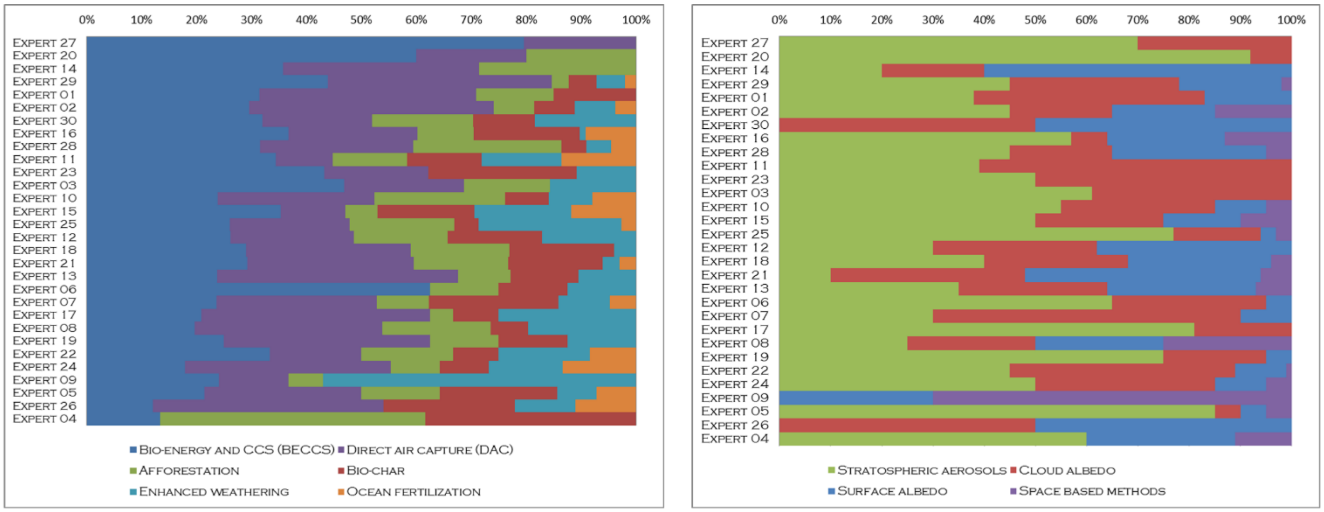


Figure 4: The share of RD&D budget allocated to CDR technologies (left) and SRM technologies (right).

Requirements for representing CDR and SRM into IAMs.

Although modeling CDR and SRM will probably be accompanied -if not preceded- by fundamental research, IAM-based analysis of climate engineering will be an important element of future assessments of policy scenarios, including 1.5°C. At the same time, models are abstractions of reality and have a limited capacity to identify specific factors which might nonetheless play a crucial role. It is important to prioritize research needs for the most fruitful areas. To get a better understanding of what can be realistically achieved through modeling exercises, we asked respondents to rate five key factors in terms of their importance for modeling CDR and SRM, as well as in terms of the difficulty of doing so. The elicited factors are: (1) 'Operational costs', which include investment and maintenance costs and define the techno-economic viability of technologies;(2) 'Effectiveness', which represents the potential to influence CO2 concentrations (for CDR) and global temperature (for SRM); (3) 'External costs and impacts', which quantify the possible negative externalities of CDR and SRM on the environment, the ecosystems, the economy; (4) 'Governance' and (5) 'Public acceptance', which pertain to institutional requirements and social acceptability.

The results are shown in Figure 5. For CDR, 'Operational costs' and 'Effectiveness' are highly important factors, which have also relatively low modeling challenges. These could represent short term opportunities for model improvements. IAMs represent both factors, but there are large uncertainties regarding current and future economics of CDR, as well their impact on carbon sinks and thus on their ability to achieve net negative CO_2 emissions. 'External costs and impacts', which are particularly important for biological CDR[23], given the interaction with land use and water resources, are important but would require significant investment since they are challenging to model. 'Governance' and 'public acceptance' –two notoriously difficult issues to incorporate in numerical models– are reported to be somewhat more challenging to correctly model than they may be relevant.

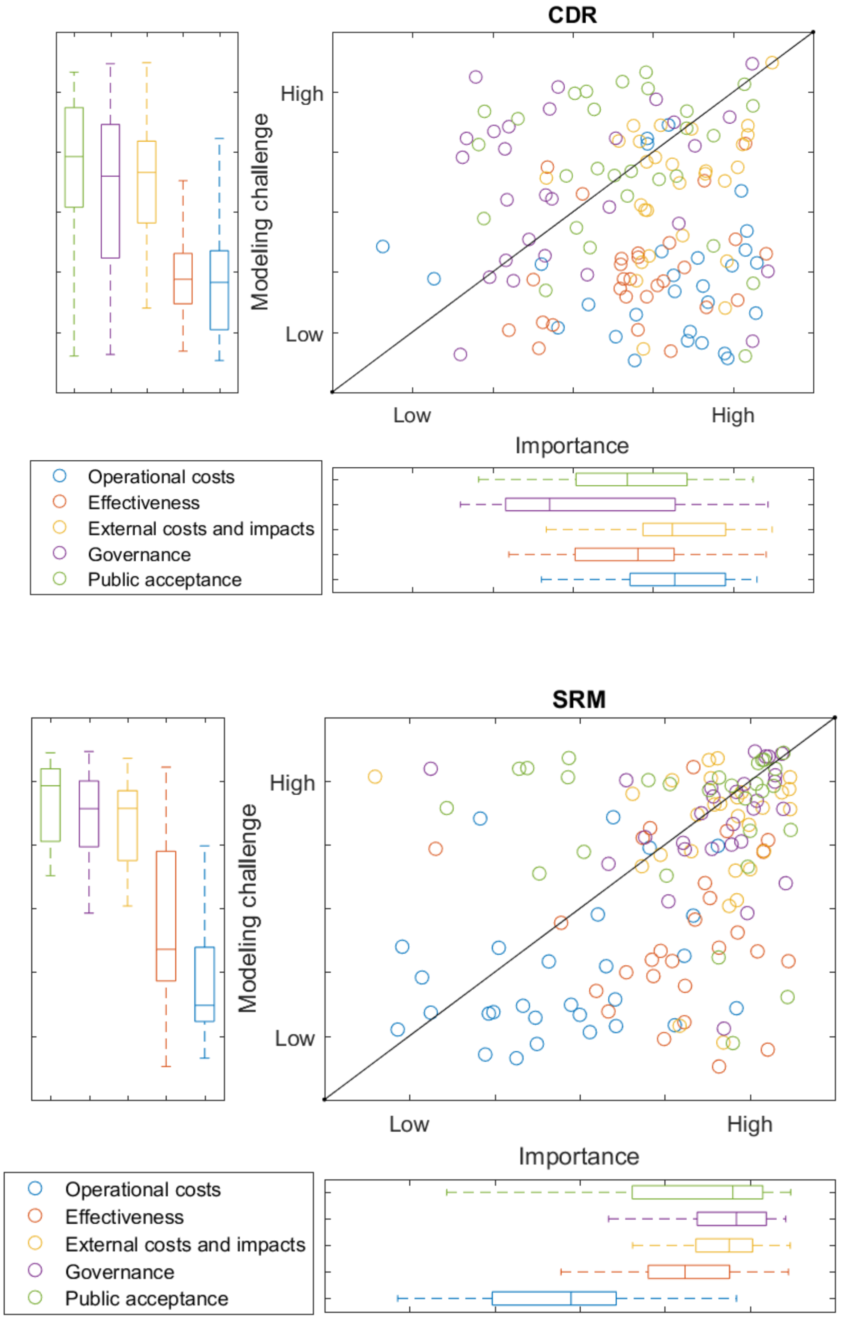


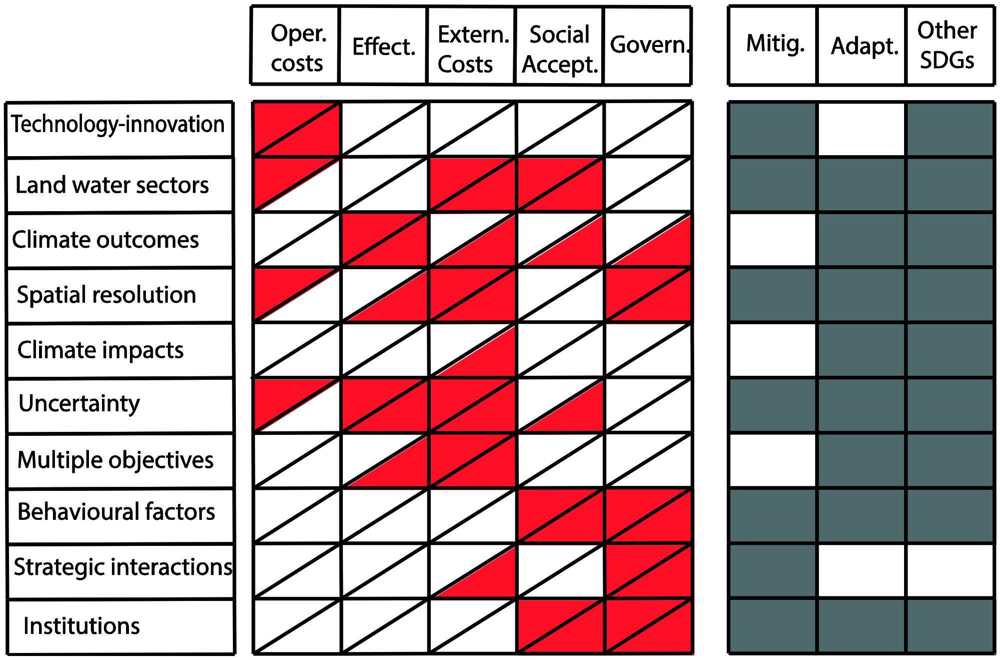
Figure 5: Importance versus challenges in modeling into IAMs for five factors, for CDR (upper panel) and SRM (lower panel). The importance scale goes from ‘Not important at all’ to ‘Extremely important’ in five steps. Similar scaling for the modeling challenge. The central panels show the scatter of experts, and two side panels provide descriptive statistics (media, interquartile ranges, and 10-90% percentiles).

SRM shows significantly more complex modeling challenges. The one exception is ‘operational costs’, which is relatively easy to properly model but also not particularly relevant: indeed SRM –especially via stratospheric aerosols– is believed to be cheap, though not as much as initially suggested[41–43] and is often assumed to have a linear cost function. ‘Effectiveness’ is a low hanging fruit, important and relatively easy to incorporate into models. All other factors –especially ‘governance’ and ‘external costs and impacts’– are deemed extremely important but also extremely challenging by most experts.

One of the two workshops which were used to recruit experts also allowed for focus group discussion around thematic sessions which covered the key elements of climate engineering. For each theme, participants identified knowledge gaps and discussed what modelling features could properly address them. Table 1 summarizes the outcome of the discussion, mapping the five factors discussed above on 10 modeling features identified from the participants.

‘Operational costs’ –which comprise investment and operation and maintenance costs, as well as cost of integration in the energy system- are key input parameters in IAMs, driving the speed and the total deployment of mitigation technologies. In order to properly represent them for both CDR and SRM, IAMs should increase the technology resolution. Indeed, IAMs typically include few CDR options, most notably BECCS and afforestation, whereas our survey identified other technological options as worth to be included. Improving the representation of technological change and innovation would allow to better represent the long term viability of climate engineering, especially CDR which is characterized by high initial costs. Endogenizing technical change - via learning curves and R&D processes- would also allow to include technological spillovers between traditional CCS based mitigation and some CDR technologies –which also rely on CCS. By doing so, models could better inform what policies should be rolled out to promote the low carbon transition most effectively, answering questions such as the targeting and timing of investments and technology subsidies to traditional versus advanced mitigation technologies. Higher spatial resolution, better representation of land-water sectors and accounting of uncertainty are also important model features for representing CDR operational costs, which vary geographically due to different capture and storage potential and are currently largely unknown.

Regarding ‘effectiveness’, a key model feature is a more precise representation of climate outcomes, beyond the standard one of global temperature increase. SRM is expected to influence various elements of the carbon-climate system, such as the hydrological cycle, extreme events, primary productivity, the potential for increased salt in precipitations, and sea level rise[39,44,45]. CDR effectiveness might be hindered by compensating mechanisms such as CO_2 outgassing from the oceans and hysteresis[26,27]. All these factors are high uncertain, and thus proper sensitivity analysis are required. Furthermore, effectiveness might not the same for different outcomes, e.g. temperature and precipitation. Especially for SRM, then, models should move away from assessing global mean temperature as the unique target, when evaluating SRM options, and include a wider set of criteria, in addition to the greater level of regional differentiation[46,47]. Inclusion of regional climate modules would be an important first step.



	Oper. costs	Effect.	Extern. Costs	Social Accept.	Govern.		Mitig.	Adapt.	Other SDGs
Technology-innovation	🟥 / 🟥	⬜ / ⬜	⬜ / ⬜	⬜ / ⬜	⬜ / ⬜		■	□	■
Land water sectors	🟥 / ⬜	⬜ / ⬜	🟥 / 🟥	🟥 / 🟥	⬜ / ⬜		■	■	■
Climate outcomes	⬜ / ⬜	🟥 / 🟥	⬜ / 🟥	⬜ / 🟥	⬜ / 🟥		□	■	■
Spatial resolution	🟥 / ⬜	⬜ / 🟥	🟥 / 🟥	⬜ / ⬜	🟥 / 🟥		■	■	■
Climate impacts	⬜ / ⬜	⬜ / ⬜	⬜ / 🟥	⬜ / ⬜	⬜ / ⬜		□	■	■
Uncertainty	🟥 / ⬜	🟥 / 🟥	🟥 / 🟥	⬜ / 🟥	⬜ / ⬜		■	■	■
Multiple objectives	⬜ / ⬜	⬜ / 🟥	🟥 / 🟥	⬜ / ⬜	⬜ / ⬜		□	■	■
Behavioural factors	⬜ / ⬜	⬜ / ⬜	⬜ / ⬜	🟥 / 🟥	🟥 / 🟥		■	■	■
Strategic interactions	⬜ / ⬜	⬜ / ⬜	⬜ / 🟥	⬜ / ⬜	🟥 / 🟥		■	□	□
Institutions	⬜ / ⬜	⬜ / ⬜	⬜ / ⬜	🟥 / 🟥	🟥 / 🟥		■	■	■

Table 1. Mapping of climate engineering 5 factors onto 10 modeling features. Red colors identify key interactions. For each cell, the upper triangle refers to CDR and the lower triangle to SRM. The 3 rightmost columns show interactions with mitigation, adaptation and other sustainable development goals. Colored cells identify modeling features which are considered key for these strategies.

As identified in the survey, proper characterization of CDR and SRM 'external costs' –on the environment, the society, etc.- is a key requirement and will be one of the most challenging tasks. Full integration of land and water sectors into IAMs, higher spatial resolution, proper accounting of uncertainty and multiple objective functions are model features considered essential for this job for both CDR and SRM. For SRM, a better representation of climate outcomes and impacts would also be needed, given the limited empirical basis of currently used climate damage functions. Disentanglement of temperature from non -temperature damages of CO_2 (e.g. ocean acidification), impacts linked to the rate of growth of temperature, etc. were identified as key modeling requirements. Moreover, some forms of SRM may interact with air quality, for example affecting ozone. Linking SRM deployment to the air quality modules, which many IAMs have integrated over the past years, is a principal next step.

Regarding 'social acceptance' of CDR and SRM, key model features are: the land-water sectors –to account for possible repercussions on food prices and water availability; behavioural factors –e.g. hidden costs to account for public opposition as well as intra and inter-generational preferences to capture equity concerns in terms of fair distribution of costs and benefits of climate engineering; and institutional factors to differentiate the willingness to invest in CDR and SRM across countries. Modeling the heterogeneity of institutions within and across countries is also important for better representing the 'governance' of climate engineering. The governance factor will be especially important for SRM, given the risk of unilateral climate engineering and of consequent 'free driving'[34], as well as the potential risks associated to termination effects[48]. IAMs should move away from evaluating globally cooperative scenarios only, and analyse more complex and fragmented coalitions accounting for potential strategic deployment of SRM in response to regional climates and other countries' climate policy decisions.

Way forward

What emerges from this scrutiny of model requirements to adequately represent CDR and SRM is a long list of desiderata. These include high geographical resolution, improved representation of climate outcomes beyond global mean temperature, interaction with air quality, multi-criteria objective functions, technological learning and spillovers, high sectoral resolution of energy, land, water and the economy, incorporation of uncertainty and risks, and radically improved and disaggregated impact functions. Addressing them all would take years of research and model advancements. Fortunately, the majority of these features are important not just for modeling climate engineering, but also for better modeling traditional mitigation and adaptation strategies, as well as other societal goals, as shown in Table1 (rightmost columns).

The IAM community has already started to deal with some of these issues. For example, many models have increased the number of macro-economic regions to provide more adequate geographical detail. The inclusion of land use modules to represent the impact of biological mitigation options, especially important for CDR, is now a common feature of many IAMs. Water modules have also been gradually phased in. The exploration of parametric and model uncertainty together is now possible thanks to newly developed sensitivity algorithms, and more efficient computational methods[49–51]. Moreover, IAMs routinely engage in multi model comparison exercises which allow different models to run a set of coordinated scenarios[52]. Climate change disaggregated impacts by different sectors -agriculture, energy, health etc- based on new econometric methods are also available, and are included into some IAMs[53]. Models are also actively engaged in improving the behavioural and institutional realism[54,55], despite their complexity. Much can be learned from alternative modeling paradigms such as agent based modeling.

Though more work is still needed, these are encouraging trends. This perspective article has highlighted the differentiated importance and requirements which CDR and SRM represent for the modeling community. Given its similarity and strict interconnection with mitigation, as well as its estimated larger contribution to the climate solution, CDR appears to be a first order priority. SRM is unique in many ways, and its representation in IAM models is important but mostly for exploratory and cursory analysis. Policy evaluation of SRM needs to account for institutional factors which might require complementary methods. Efforts towards representation of climate engineering in IAMs should also not crowd out the much needed work to evaluate short term policy objectives, for which both options would not be relevant. The current hybrid international policy architecture, which relies on a vast array of often different and at times in conflict policy tools, requires vast modeling investments to be adequately represented and evaluated.

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Supplementary online material

Description of scenarios presented to survey respondents

BoxS1: Policy Scenarios Considered in the Survey:

- 3°C Bottom up: A world characterized by fragmented, national policy actions consistent with the proposed INDCs for the year 2030, and extrapolated forward at the same level of ambition. Let's assume these policies will lead to a 2100 temperature increase of 3°C. This scenario entails a temperature reduction from baseline of 1-2°C in 2100.
- 2°C Bottom up: A world characterized by fragmented, national policy actions with a long term temperature goal of 2°C (with 50% chances). This scenario entails a temperature reduction from baseline of 2-3°C in 2100.
- 2°C Top down: A world characterized by coordinated, global policy actions with a long term temperature goal of 2°C (with 50% chances). This scenario entails a temperature reduction from baseline of 2-3°C in 2100.
- 1.5°C Top down: A world characterized by coordinated, global policy actions with a long term temperature goal of 1.5°C (with 50% chances). This scenario entails a temperature reduction from baseline of 2.5-3.5°C in 2100.

Additional figures

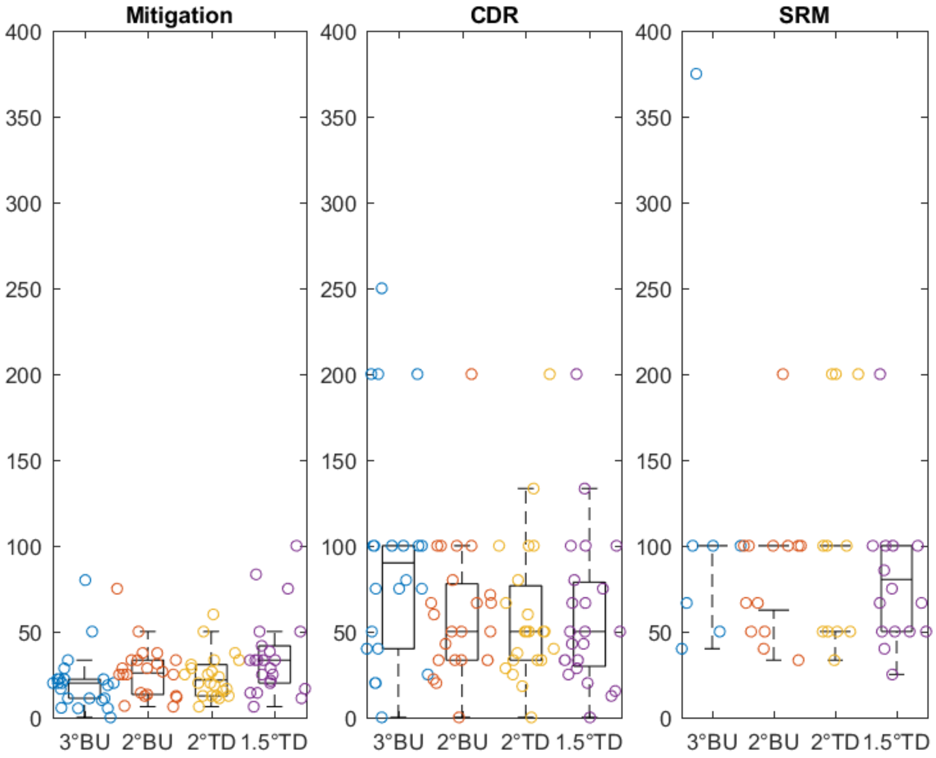

Figure S1. Uncertainty (range around the mean over mean, as provided by respondents, in percentage points) of relative contribution of mitigation, CDR and SRM (See Figure 1)

Figure S2: Timing of initial deployment (10% of maximum deployment) of CDR (left panel) and SRM (right panel) across policy scenarios. The bars indicate the counting of experts for the different time bins.

Figure S3: Relative share of RD&D budget allocated to research (light colors) and development and demonstration (dark colors) for CDR (blue) and SRM (orange).

Survey participants

Respondents to the survey were selected in the following way.

First, a workshop was organized in early November 2016 by Fondazione Eni Enrico Mattei (FEEM), a private research organization devoted to research on climate change and sustainability. The workshop consisted of 22 participants, 12 of which took the survey. Agenda and details of the meeting are accessible here http://www.feem.it/getpage.aspx?id=8732&sez=Events&padre=79.

A second larger workshop was organized by the Kiel Institute for the World Economy, sponsored by the German Research Foundation (DFG) Priority Programme (SPP) 1689, which examines the risks and side effects of "Climate Engineering". 81 researchers attended, and 11 filled in the online questionnaire. Details about the meeting can be found here http://www.spp-climate-engineering.de/SPP1689WorkshopKielNov16.html

Finally, a list of 18 experts was selected based on number of Google Scholar citation (>80) for CDR and SRM paper. Out of 18, 5 responded to the survey. Two additional respondents provided anonymous replies. The following table list the experts, their affiliation, the source of selection and their field of interest.

Name	**Affiliation**	**Participation**	**Expertise**
Celine Guivarch	CIRED	1st workshop	economics,climate policy,integrated assessment modeling
Helene Muri	University of Oslo	1st workshop	climate science
Johannes Emmerling	FEEM	1st workshop	economics,climate policy,integrated assessment modeling
Juan Moreno-Cruz	Georgia Tech University	1st workshop	economics,climate policy,integrated assessment modeling,engineering
Laurent Drouet	FEEM	1st workshop	integrated assessment modeling
Marco Vitali	Politecnico di Milano	1st workshop	engineering
Martin Quaas	Kiel University	1st workshop	economics
Sabine Fuss	MCC	1st workshop	economics
Soheil Shayegh	FEEM	1st workshop	economics,climate policy,integrated assessment modeling,engineering
Thomas Lontzek	RWTH Aachen University	1st workshop	economics,integrated assessment modeling
Vasso Manoussi	FEEM	1st workshop	economics
Wilfried Rickels	Kiel Institute for the World Economy	1st workshop	economics,integrated assessment modeling
Annika Vergin	Bundeswehr	2nd workshop	other
Detlef van Vuuren	PBL and University of Utrecht	2nd workshop	integrated assessment modeling
Elmar Kriegler	PIK	2nd workshop	integrated assessment modeling

Fabian Reith	GEOMAR	2nd workshop	climate science
Felix Wittstock	UFZ	2nd workshop	climate policy,other
Hermann Held	University of Hamburg	2nd workshop	economics,climate science,integrated assessment modeling,environmental science
Jens Hartmann	University of Hamburg	2nd workshop	climate science,integrated assessment modeling,environmental science,other
Jesse Reynolds	Tilburg University	2nd workshop	climate policy
Smith	The University of Aberdeen	2nd workshop	environmental science
Thomas Leisner	Karlsruhe Institute of Technology	2nd workshop	environmental science
Tobias Schad	Karlsruhe Institute of Technology	2nd workshop	climate science
Douglas MacMartin	California Institute of Technology	Expert list	climate science,engineering
Kate Ricke	University of California San Diego	Expert list	climate science,climate policy
Ken Caldeira	Carnegie Institution for Science	Expert list	climate science,environmental science
Keywan Riahi	IIASA	Expert list	economics,integrated assessment modeling,environmental science,engineering
Nilay Shah	Imperial College	Expert list	engineering
Anonymous			climate policy
Anonymous			

Table S1. List of survey respondents, affiliations and selection procedure. The respondents order is not the one shown in some of the Figures of the paper.

Figure S4 shows the distribution of the focus of research of the survey respondents. The chart indicates that the majority of respondents list mitigation as their primary research field, while few focus on impacts and adaptation. For SRM the sample is split in half between experts who primarily do research on SRM and those who don’t. CDR has a more smooth distribution, with the majority of experts partly focusing their research work on CDR.

Figure S4. Distribution of main field of research of the survey respondents, across disciplines. The scale 1-5 represents the extent of the focus of research, with 1 meaning ‘This is not the focus of my research’ and 5 meaning ‘This is the main focus of my research’

Focus Group

As discussed in the paper, the first workshop included a focused group to discuss in detail the model requirements for an adequate representation of CDR and SRM. In addition to the 12 people who took the survey and are listed in Table S1, the following additional researchers provided input to the discussion:

Valentina Bosetti (Bocconi University and FEEM),Christine Gutekunst (Politecnico di Milano and FEEM), David Keith (Harvard University), Mark Lawrence (IASS), Fabien Ramos (European Commission), Massimo Tavoni (Politecnico di Milano and FEEM)

Survey text

Q1 Please read this consent document carefully Title of Study: Climate Engineering Survey Purpose of the research study: We elicit experts' judgments regarding potential and research priorities for Climate Engineering Technologies. What you will be asked to do in the study: You will be asked to answer a series of questions over various future scenarios of climate change policy. We will also collect basic information about yourself (expertise, etc.). Time required: Approximately 15 minutes. Risks and Benefits: There are no risks beyond everyday life associated with the experiment. Compensation: None. Confidentiality: Your identity will be kept confidential to the extent provided by law. Voluntary participation: Your participation in this study is completely voluntary. There is no penalty for not participating. You may also refuse to answer any of the questions we ask you. Right to withdraw from the study: You have the right to withdraw from the study at any time without consequence. You will be deemed as not completing the study. Informed Consent: You can print a copy of this informed consent form. Whom to contact if you have questions about the study: Massimo Tavoni (massimo.tavoni@feem.it) and Valentina Bosetti (valentina.bosetti@feem.it) Agreement: I have read the procedure described above. I voluntarily agree to participate in the procedure and I have received an informational sheet including the title of this study, the name of the principal investigator and contact information, along with the contact information for the IRB.

Q81 This survey aims at eliciting the opinion of experts about the prospects of climate engineering (CE) technologies (both carbon dioxide removal CDR and solar radiation management SRM) as climate change strategies, as well as the research gaps needed to provide robust impact assessment. We will use the acronyms CE, CDR and SRM throughout the survey.

Q60 As a reference scenario, let's consider a world where climate change is not an issue (e.g. the impacts are zero). Baseline scenarios of this kind have been estimated to yield end of the century radiative forcings between 6 and 8.5 W/m^2 and temperature increase between 4 and 5°C (IPCC AR5, WGIII, Figures 6.6 and 6.13). Against this counterfactual, let's consider 4 policy scenarios with different levels of ambition and implementation:

- 3°C Bottom up: A world characterized by fragmented, national policy actions consistent with the proposed INDCs for the year 2030, and extrapolated forward at the same level of ambition. Let's assume these policies will lead to a 2100 temperature increase of 3°C. This scenario entails a temperature reduction from baseline of 1-2°C in 2100.
- 2°C Bottom up: A world characterized by fragmented, national policy actions with a long term temperature goal of 2°C (with 50% chances). This scenario entails a temperature reduction from baseline of 2-3°C in 2100.
- 2°C Top down: A world characterized by coordinated, global policy actions with a long term temperature goal of 2°C (with 50% chances). This scenario entails a temperature reduction from baseline of 2-3°C in 2100.
- 1.5°C Top down: A world characterized by coordinated, global policy actions with a long term temperature goal of 1.5°C (with 50% chances). This scenario entails a temperature reduction from baseline of 2.5-3.5°C in 2100.

Q73 For each of the 4 scenarios, what do you think will be the relative contribution of Mitigation, CDR and SRM to temperature reduction in 2100 (in percentage points)? Please provide your best guess, along with a range spanning scenarios of high and low deployment of CE (both for CDR and SRM). This range is meant to span the 10th-90th percentiles of future realizations.The best guess columns should sum up to 100.

	Best guess (1)	Range (+/-) (2)	Best guess (1)	Range (+/-) (2)	Best guess (1)	Range (+/-) (2)	Best guess (1)	Range (+/-) (2)
Mitigation (1)								
CDR (2)								
SRM (3)								

Q50 For each of the 4 scenarios, by which year do you think CDR and SRM will be deployed at scale (eg. 10% of their maximum use in each scenario) ?As before, please provide your best guess, along with the range estimate. The range unit is number of years.

	Best guess (1)	Range (+/-) (2)	Best guess (1)	Range (+/-) (2)	Best guess (1)	Range (+/-) (2)	Best guess (1)	Range (+/-) (2)
CDR (1)								
SRM (2)								

Q69 Focusing on CDR, please rank the following technologies in terms of their deployment potential in a scenario of large scale deployment

______ Bio-energy and CCS (BECCS) (1)
______ Bio-char (2)
______ Afforestation (3)
______ Direct Air Capture (11)
______ Enhanced Weathering (12)
______ Ocean fertilization (13)

Q70 Focusing on SRM, please rank the following technologies in terms of their deployment potential in a scenario of large scale deployment

______ Surface albedo (1)
______ Cloud albedo (2)
______ Stratospheric aerosols (3)
______ Space based methods (11)

Q75 Which regions/countries do you think are most likely to invest in CDR and SRM in a scenario with deployment of CE ?

	Extremely likely (1)	Somewhat likely (2)	Neither likely nor unlikely (3)	Somewhat unlikely (4)	Extremely unlikely (5)	Extremely likely (1)	Somewhat likely (2)	Neither likely nor unlikely (3)	Somewhat unlikely (4)	Extremely unlikely (5)
EU (1)	○	○	○	○	○	○	○	○	○	○
USA (2)	○	○	○	○	○	○	○	○	○	○
Other OECD (3)	○	○	○	○	○	○	○	○	○	○
China (4)	○	○	○	○	○	○	○	○	○	○
India (5)	○	○	○	○	○	○	○	○	○	○
Brazil (6)	○	○	○	○	○	○	○	○	○	○
Energy exporting (7)	○	○	○	○	○	○	○	○	○	○
Other developing (8)	○	○	○	○	○	○	○	○	○	○

Q78 Let's now focus on research in climate engineering options. Which factors regarding CDR and SRM should be further researched and understood?

	Extremely important (1)	Very important (2)	Moderately important (3)	Slightly important (4)	Not important at all (5)	Extremely important (1)	Very important (2)	Moderately important (3)	Slightly important (4)	Not important at all (5)
Operational costs (1)	○	○	○	○	○	○	○	○	○	○
External costs and impacts (2)	○	○	○	○	○	○	○	○	○	○
Effectiveness (3)	○	○	○	○	○	○	○	○	○	○
Governance (4)	○	○	○	○	○	○	○	○	○	○
Public acceptance (5)	○	○	○	○	○	○	○	○	○	○

Q77 In your opinion, which factors can be more or less easily incorporated in an integrated assessment of CDR and SRM which accounts for technical, economic and environmental factors?

	Extremely easy (1)	Somewhat easy (2)	Neither easy nor difficult (3)	Somewhat difficult (4)	Extremely difficult (5)	Extremely easy (1)	Somewhat easy (2)	Neither easy nor difficult (3)	Somewhat difficult (4)	Extremely difficult (5)
Operational costs (1)	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
External costs and impacts (2)	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
Effectiveness (3)	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
Governance (4)	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
Public acceptance (5)	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍

Q47 Suppose you have to decide how to allocate a budget of 100 to RD&D in climate engineering over the next 10-20 years globally. How would you distribute it?

_______ CDR: research (1)
_______ CDR: development and demonstration (2)
_______ SRM: research (3)
_______ SRM: development and demonstration (4)

Q48 Focusing on CDR, how would you distribute the indicated RD&D budget among technologies?

______ Bio-energy and CCS (BECCS) (1)
______ Bio-char (2)
______ Afforestation (3)
______ Direct Air Capture (11)
______ Enhanced Weathering (12)
______ Ocean fertilization (13)

Q49 Focusing on SRM, how would you distribute the indicated RD&D budget among technologies?

______ Surface albedo (1)
______ Cloud albedo (2)
______ Stratospheric aerosols (3)
______ Space based methods (11)

Q95 DEMOGRAPHICS Please enter your name and surname. Any personal information will be anonymized in the presentation of results.

Q96 Please choose your professional affiliation(s)

- ☐ Government (1)
- ☐ NGO (2)
- ☐ Research institution (3)
- ☐ Private sector (4)
- ☐ other (5) ____________________

Q29 Have you been involved in any report of the IPCC? If yes, select which working group(s)

- ☐ WG I (1)
- ☐ WG II (2)
- ☐ WG III (3)

Q97 Please enter your field(s) of expertise

- ☐ economics (1)
- ☐ climate science (2)
- ☐ climate policy (3)
- ☐ integrated assessment modeling (4)
- ☐ environmental science (5)
- ☐ engineering (6)
- ☐ other (7) ____________________

Q98 What is your level of expertise in the following fields?

Mitigation (1)	○	○	○	○	○
CDR (2)	○	○	○	○	○
SRM (3)	○	○	○	○	○
Impacts and adaptation (4)	○	○	○	○	○

Q99 Which aspects of CDR and SRM are you more familiar with?

	Extremely knowledgeable (1)	Very knowledgeable (2)	Moderately knowledgeable (3)	Slightly knowledgeable (4)	Not knowledgeable at all (5)	Extremely knowledgeable (1)	Very knowledgeable (2)	Moderately knowledgeable (3)	Slightly knowledgeable (4)	Not knowledgeable at all (5)
Operational costs (1)	○	○	○	○	○	○	○	○	○	○
External costs and impacts (2)	○	○	○	○	○	○	○	○	○	○
Effectiveness (3)	○	○	○	○	○	○	○	○	○	○
Governance (4)	○	○	○	○	○	○	○	○	○	○
Public acceptance (5)	○	○	○	○	○	○	○	○	○	○
Other (6)	○	○	○	○	○	○	○	○	○	○

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