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LETTER

Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs

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Abstract

There are major concerns about the sustainability of large-scale deployment of carbon dioxide removal (CDR) technologies. It is therefore an urgent question to what extent CDR will be needed to implement the long term ambition of the Paris Agreement. Here we show that ambitious near term mitigation significantly decreases CDR requirements to keep the Paris climate targets within reach. Following the nationally determined contributions (NDCs) until 2030 makes 2 °C unachievable without CDR. Reducing 2030 emissions by 20% below NDC levels alleviates the trade-off between high transitional challenges and high CDR deployment. Nevertheless, transitional challenges increase significantly if CDR is constrained to less than 5 Gt CO_2 a^{-1} in any year. At least 8 Gt CO_2 a^{-1} CDR are necessary in the long term to achieve 1.5 °C and more than 15 Gt CO_2 a^{-1} to keep transitional challenges in bounds.

Introduction

The Paris Agreement adopted by the member states of the United Nations Framework Convention on Climate Change (UNFCCC) in 2015 was a milestone in international climate policy negotiations. For the first time, a large number of nation states laid out concrete plans for their short-term contributions until 2030 towards the goal to stay well below 2 °C and pursue efforts to limit warming to 1.5 °C. These nationally determined contributions (NDCs) have to be ratcheted up in the coming years to become more consistent with the long-term goals. In their current formulation the NDCs lead to CO_2 emissions in 2030 that are 14 Gt higher than cost-effective scenarios consistent with well below 2 °C (Rogelj *et al* 2016). Medium- and long-term strategies are much less concrete. Plausible internally consistent pathways are laid out by scenarios that were assessed in the 5th Assessment Report (AR5) of the IPCC (Clarke *et al* 2014). Almost all of these scenarios rely heavily on large-scale carbon dioxide removal (CDR) on the order of several to several tens of Gt CO_2 a^{-1} (Clarke *et al* 2014). For comparison, the current annual amount of CO_2 used for enhanced oil recovery is 70 Mt CO_2 (IEA 2014). Annual sequestration of 5 Gt CO_2 would require a carbon capture and storage (CCS) industry of the size of today's oil industry (IEA 2016). The dependency on CDR can only be expected to increase for 1.5 °C scenarios (Rogelj *et al* 2015). However, these technologies are afflicted with three types of uncertainties. First, there are technical uncertainties like technical feasibility, potential, and economic costs. Second, adverse side effects and sustainability implications could substantially limit their potential (Williamson 2016). And finally, the political feasibility to build institutions for net carbon dioxide removal is by no means given. In addition, the large-scale deployment of CDR leads to a peak in carbon removal towards the end of the century. This may cause risks of climate change irreversibility due to temperature overshoot and higher intergenerational imbalance (Obersteiner *et al* 2018).

The prevalence of CDR in AR5 2 °C scenarios on the one hand and the risks and uncertainties associated with CDR technologies on the other hand give rise to the question how much CDR is actually needed to achieve climate targets like well below 2 °C or even 1.5 °C (Fuss *et al* 2016). Since short-term mitigation strategies are decided on in the coming years despite insufficient knowledge regarding CDR, an analysis of the trade-off between short-term policy costs and long-term CDR requirement is necessary in order to make these decisions and find a robust strategy.

Current scenarios cannot answer these questions. If CDR is available in models, it is not exclusively used as a last resort, but also driven by economic reasons. These lead to a higher exploitation of the potential beyond minimum requirements. To assess the importance of CDR, some studies excluded it completely or studied one limited case (Kriegler *et al* 2014, Luderer *et al* 2013). Only few of the 2 °C scenarios in the AR5 database (IPCC 2015) derived solutions without CDR because most models assessed the quick and deep emission reductions that would be necessary as technically infeasible. Other studies pointed out that delayed climate policy reduces the remaining permissible emissions budget and therefore enhances the demand for CDR (Riahi *et al* 2013).

To our knowledge, this study is the first to identify minimum CDR requirements for reaching the well below 2 °C and possibly 1.5 °C goal laid down in the Paris Agreement. We do this by exploring the trade-offs between near-term climate policy ambition, transitional challenges, and CDR availability. It is intuitively clear that less effort in one dimension will increase tension in the other two (see figure 2(*b*)). We quantify these trade-offs to identify the benefits of strengthening the NDCs. This information is directly relevant for the global stock take assessing the consistency of current climate policy plans with the ambition of the Paris Agreement and for guiding decisions on the strengthening and progression of NDCs.

Methods

We use the global multi-regional energy-economy-climate model REMIND (Bauer *et al* 2012, Luderer *et al* 2015) to determine cost-effective emission and technology pathways. Scenarios reach a cumulative CO_2 budget from 2011–2100 of either 400 Gt CO_2 which is consistent with a 50% chance to remain below 1.5 °C temperature increase above pre-industrial times in 2100, or 1000 Gt CO_2, consistent with a 66% chance to remain below 2 °C in most scenarios, except of those with a high forcing overshoot.

Bioenergy (Obersteiner 2001, Klein *et al* 2014) and direct air capture of CO_2 from ambient air (DAC, Keith *et al* 2006), both in combination with CCS, and re- and afforestation (Humpenöder *et al* 2014) are available as CDR technologies. Bioenergy with CCS (BECCS) is the CDR technology most widely used in the AR5 scenarios and the only CDR technology that provides energy instead of consuming it. BECCS is based on the assumption that carbon-neutral bioenergy can be turned carbon negative by capturing the emissions arising during combustion or the refinery process. DAC captures CO_2 from ambient air, which requires large amounts of heat and electricity. An estimated 430–570 $ t^{-1} CO_2 makes it a rather expensive option compared to both BECCS at 36 $ t^{-1} CO_2 and afforestation at 24 (18–30) $ t^{-1} CO_2 (Smith *et al* 2015), but on the upside DAC is less dependent on the location and requires only little land.

All scenarios follow policies consistent with current and planned policies as reflected in the Cancun Agreement (UNFCCC 2010) until 2020. After 2020, it is assumed that global cooperative mitigation starts, represented by an exponentially increasing globally uniform carbon price (figure 1(*b*)). Along the policy dimension, we consider different levels of short-term policy ambition from 2021–2030, i.e. different levels of carbon price. During this time, CDR is not available. After 2030, CDR becomes available and the carbon price is adjusted such that the climate target in 2100 is met. In a second scenario dimension, we vary the maximal annual CDR availability between 0 and 20 Gt CO_2 a^{-1}. This two-staged approach generally leads to a discontinuity of the carbon price in 2030 (see figure 1). If the short-term policy was insufficient for the level of CDR availability post-2030, the CO_2 price will jump to a higher level. If the policy was overambitious, the CO_2 price may drop (see figure 1(*b*)). In addition, we consider cost-effective benchmark scenarios with global mitigation including CDR starting in 2021. Figure 1(*b*) shows the resulting long-term CO_2 prices as a function of short-term prices for different levels of CDR availability. We indicated the short-term price trajectory that would lead to an outcome consistent with the NDCs determined in the Paris Agreement, as identified by (Fawcett *et al* 2015). In order to assess uncertainties of short- and medium-term challenges associated with different levels of CDR availability, we vary socio-economic assumptions as described in the shared socio-economic pathways (SSPs, (Riahi *et al* 2016), see SI available at stacks.iop.org/ERL/13/044015/mmedia).

Results

We find that very ambitious near-term mitigation action can keep the well-below 2 °C target within reach without CDR, albeit at significant near-term and transitional challenges (figure 2). Near-term challenges are characterized by the 2030 emission level. As an indicator for transitional challenges, we use average reduction rates of CO_2 emissions from fossil fuel combustion and industry processes between 2030 and 2050.

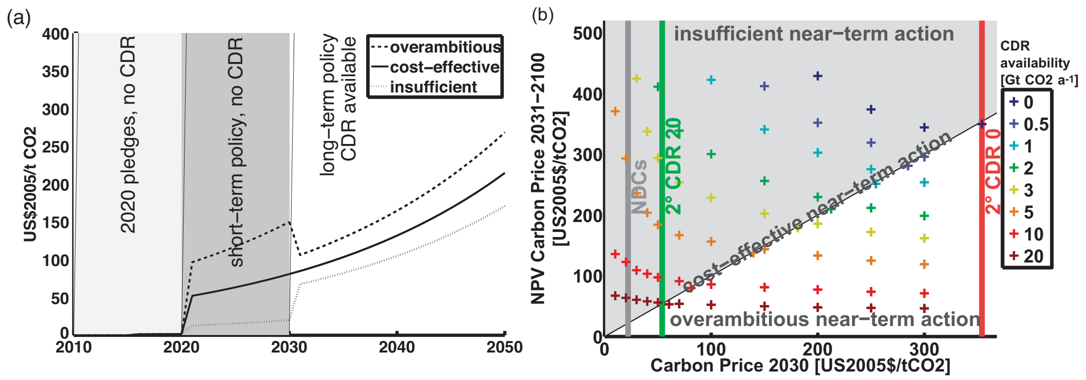

Figure 1. (*a*) Global carbon prices in 2 °C scenarios for three exemplary short-term policies and levels of CDR availability. (*b*) Global carbon price in 2030 vs. global net present value carbon price 2031–2100 in 2 °C scenarios for different levels of CDR availability. The diagonal indicates the cost-effective scenarios where the net present value carbon price remains constant. The shaded area above this line indicates scenarios with insufficient near-term ambition. The vertical lines indicate short-term price trajectories consistent with the NDCs (grey) and with cost-effective 2 °C pathways using 20 Gt CO_2 $^{-1}$ CDR (green) and no CDR (red).

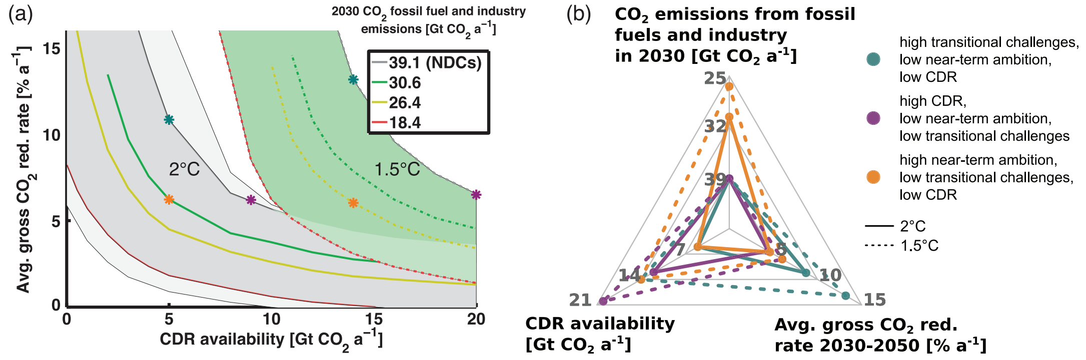

Figure 2. Trade-off between short-term mitigation ambition, transitional challenges, and CDR availability. (*a*) CDR availability vs. average gross CO_2 reduction rate 2030–2050 for the short-term policy levels emerging from the cost-effective benchmark scenarios indicated in figures 1+3. The lighter funnel indicates uncertainty due to socio-economic pathway variations. b) Trade-off between the three dimensions of short-term mitigation ambition, transitional challenges, and CDR availability for achieving 2 °C (solid lines) and 1.5 °C (dashed lines).

When following the NDCs until 2030, achieving 2 °C without CDR will not be possible anymore. At less than 5 Gt CO_2 a^{-1} CDR, medium-term challenges increase substantially. Limiting end-of-century temperature increase to 1.5 °C is not possible anymore without CDR. At least 8 Gt CO_2 a^{-1} CDR are necessary, with medium-term challenges increasing significantly if less than 15 Gt CO_2 a^{-1} CDR are available.

There are historic examples where annual CO_2 emission reduction rates of 2%–3% have been achieved in some countries for several consecutive years (Riahi *et al* 2013). Even when 20 Gt CO_2 a^{-1} CDR are available, this emission reduction rate is too small to achieve 2 °C after following the NDCs. For an average annual CO_2 emission reduction rate of 4% between 2030–2050 to be in line with a cost-effective well-below 2 °C pathway, following the NDCs would require 16 Gt CO_2 a^{-1} CDR.

Strengthening the short-term ambition by 20%, i.e. to 31 Gt CO_2 a^{-1} in 2030, could halve this CDR requirement to 8 Gt CO_2 a^{-1} CDR. Very high short-term ambition (18 CO_2 a^{-1} in 2030) could reduce this again by a factor of four to 2 Gt CO_2 a^{-1} CDR. Reaching 1.5 °C at 4% annual CO_2 emission reduction rate requires both very high near-term ambition of more than halving 2030 CO_2 emissions as compared to the NDCs and high levels of CDR of at least 12 Gt CO_2 a^{-1}.

Short-term climate policy ambition is the defining factor for future CDR requirements. Following the NDCs until 2030 forces future generations to decide between high CDR deployment and high CO_2 emission reduction rates to still achieve the well-below 2 °C target. Strengthening short-term ambition by 20% attenuates this trade-off, halving either medium-term challenges or CDR requirements.

Transitional challenges increase both with decreasing CDR availability and with decreasing short-term policy ambition (figure 3, upper panel). A combination of weak short-term policy and little CDR availability makes the 2 °C target unachievable. Total mitigation costs on the other hand are mainly determined by the level of CDR availability (figure 3, middle panel). Only close to the 'achievability frontier' are mitigation costs very sensitive to already small changes in

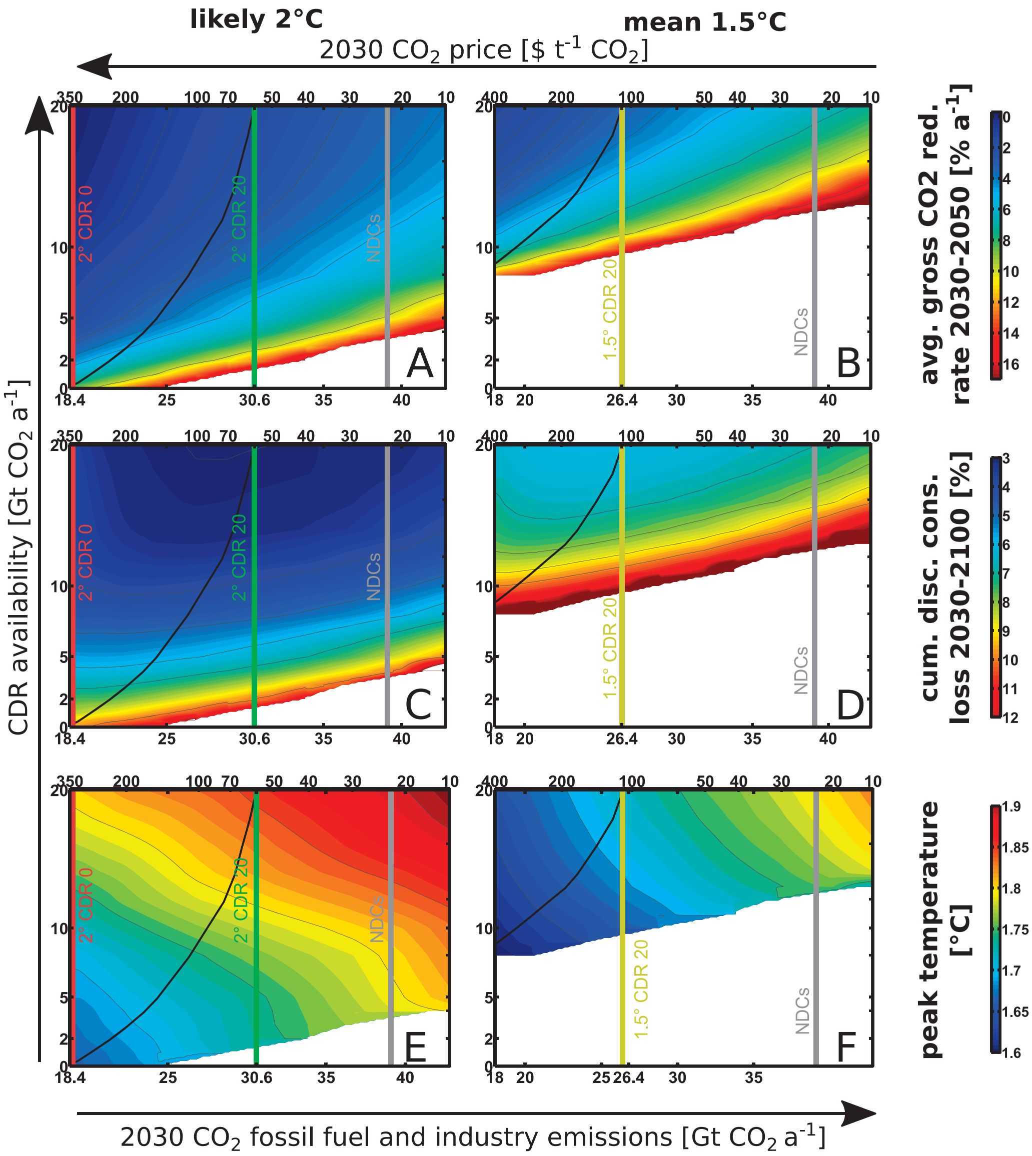

Figure 3. (A+B): average gross CO_2 emission reduction rate 2030–2050, indicator for transitional challenges. (C+D): cumulative discounted consumption losses (cumulated between 2030–2100 using a discount rate of 5% per year), indicator for total economic costs. (E+F): peak temperature, indicator for climate risks. All indicators are shown for 2 °C (left panel) and 1.5 °C (right panel) scenarios. The color code denotes the value of the indicators. They depend on short-term policy ambition (*x*-axis) and CDR availability (*y*-axis). Short-term policy ambition can be measured in terms of 2030 CO_2 emissions from fossil fuels and industry (lower *x*-axis) or 2030 CO_2 price (upper *x*-axis). The black line shows the cost-effective scenarios. The grey bar indicates the emissions resulting from the NDCs, and the colored bars indicate the emissions from the cost-effective scenarios 20 Gt CDR, 1.5 °C (yellow), 20 Gt CDR, 2 °C (green), no CDR, 2 °C (red).

short-term policy (Luderer *et al* 2013). Here we define total mitigation costs as global cumulative discounted consumption losses (cumulated between 2030 and 2100 using a discount rate of 5% per year). Consumption losses are measured relative to a no policy baseline. These do not include climate damages, thus not taking into account mitigation benefits, co-benefits, and side-effects. Please note that in the AR5, the time horizon for cumulative mitigation costs is usually 2015–2100, which leads to lower cost numbers.

More CDR deployment leads to lower economic challenges both near- and long-term. However, in addition to higher technical and sustainability risks, it also increases peak temperature and thus climate risks (figure 3, lower panel). Peak temperature increases by 0.006°–0.009° per annual Gt CO_2 CDR available and by 0.005–0.007° per additional Gt CO_2 emitted in 2030.

Discussion and conclusion

These results indicate that short-term mitigation would need to be increased at least to the level of the cost-effective 2° CDR 20 scenario, corresponding to about 31 Gt CO_2 from fossil fuel use and industry in 2030, in order to attenuate the trade-off between transitional challenges in the period 2030-50 and required CDR availability. Delaying short-term efforts relative to the cost-effective benchmark case increases future mitigation challenges. In such cases of delayed near term mitigation effort (left of black line in figure 3), reaching 2 °C then requires either a faster decarbonization post 2030 associated with higher transitional and long-term economic costs or the deployment of larger amounts of CDR associated with higher technological, ecological and climate risks. For temperatures to return to 1.5 °C towards the end of the century a combination of all three efforts, ambitious near-term mitigation, high CDR deployment, and high CO_2 emission reduction rates associated with high economic costs is necessary.

We explored the robustness of our results with a sensitivity analysis regarding socio-economic development (see SI for details). A more sustainable socio-economic development could reduce short-term and transitional challenges and the minimum CDR requirements (figure S4). However, even under such optimistic assumptions, 2 °C would remain out of reach if the NDCs were not to be strengthened. Abundant fossil fuels and high economic growth could even increase the dependency on large-scale CDR deployment, making the achievement of the Paris goals almost impossible without CDR (SI).

Even though more optimistic assumptions on energy efficiency, bioenergy availability, or the amount of hard-to-avoid emissions from agriculture, transport, and buildings could change the exact numbers, the risks and risk aversion strategies identified here are robust. Therefore, a combination of more short-term efforts and at least a certain level of CDR deployment appears necessary. This result and the high level of CDR needed to achieve 1.5 °C point towards the need for more research regarding technical and social feasibility and limitations of different CDR technologies.

The challenge will be to find a level of effort that navigates between short-term costs, transitional challenges, and CDR deployment at the same time. Ambitious short-term mitigation will be needed to uphold the long-term goal of the Paris Agreement and attenuate the trade-off between high economic costs and large-scale CDR.

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References

Bauer N, Baumstark L and Leimbach M 2012 The REMIND-R model: the role of renewables in the low-carbon transformation–first-best vs. second-best worlds *Clim. Change* **114** 145–68

Clarke L *et al* 2014 Assessing transformation pathways *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer *et al* (Cambridge: Cambridge University Press)

Fawcett A A *et al* 2015 Can Paris pledges avert severe climate change? *Science* **350** 1168–9

Fuss S *et al* 2016 Research priorities for negative emissions *Environ. Res. Lett.* **11** 115007

Humpenöder F, Popp A, Dietrich J P, Klein D, Lotze-Campen H, Bonsch M, Bodirsky B L, Weindl I, Stevanovic M and Müller C 2014 Investigating afforestation and bioenergy CCS as climate change mitigation strategies *Environ. Res. Lett.* **9** 064029

IEA 2014 *CCS 2014: What Lies in Store for CCS?* (Paris: OECD/IEA)

IEA 2016 *World Energy Outlook 2016* (Paris: International Energy Agency)

IPCC 2015 AR5 Scenario Database *AR5 Scenario Database* (https://tntcat.iiasa.ac.at/AR5DB/)

Keith D W, Ha-Duong M and Stolaroff J K 2006 Climate Strategy with CO_2 Capture from the Air *Clim. Change* **74** 17–45

Klein D *et al* 2014 The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE *Clim. Change* **123** 705–18

Kriegler E *et al* 2014 The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies *Clim. Change* **123** 353–67

Luderer G *et al* 2015 *Description of the REMIND Model (Version 1.6)* (Rochester, NY: Social Science Research Network)

Luderer G, Pietzcker R C, Bertram C, Kriegler E, Meinshausen M and Edenhofer O 2013 Economic mitigation challenges: how further delay closes the door for achieving climate targets *Environ. Res. Lett.* **8** 034033

Obersteiner M 2001 Managing Climate Risk *Science* **294** 786b–787

Obersteiner M *et al* 2018 How to spend a dwindling greenhouse gas budget *Nat. Clim. Change* **8** 7–10

Riahi K *et al* 2015 Locked into Copenhagen pledges—Implications of short term emission targets for the cost and feasibility of long term climate goals *Technol. Forecas. Soc. Change* **90** 8–23

Riahi K *et al* 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68

Rogelj J, den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K and Meinshausen M 2016 Paris Agreement climate proposals need a boost to keep warming well below 2 °C *Nature* **534** 631–9

Rogelj J, Luderer G, Pietzcker R C, Kriegler E, Schaeffer M, Krey V and Riahi K 2015 Energy system transformations for limiting end-of-century warming to below 1.5 °C *Nat. Clim. Change* **5** 519–27

Smith P *et al* 2015 Biophysical and economic limits to negative CO_2 emissions *Nat. Clim. Change* **6** 42–50

UNFCCC 2010 The Cancun Agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention (http://unfccc.int/documentation/decisions/items/3597.php)

Williamson P 2016 Emissions reduction: scrutinize CO_2 removal methods *Nature* **530** 153–5