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IOP Publishing | Environmental Research Letters
Environ. Res. Lett. 8 (2013) 034033 (8pp) | doi:10.1088/1748-9326/8/3/034033

Economic mitigation challenges: how further delay closes the door for achieving climate targets

Gunnar Luderer[1], **Robert C Pietzcker**[1], **Christoph Bertram**[1], **Elmar Kriegler**[1], **Malte Meinshausen**[1,2] and **Ottmar Edenhofer**[1,3,4]

[1] Potsdam Institute for Climate Impact Research, D-14473 Potsdam, Germany
[2] School of Earth Sciences, University of Melbourne, Victoria 3010, Australia
[3] Technische Universität Berlin, D-10632 Berlin, Germany
[4] Mercator Research Institute on Global Commons and Climate Change, D-10829 Berlin, Germany

E-mail: luderer@pik-potsdam.de

Received 5 May 2013
Accepted for publication 28 August 2013
Published 17 September 2013
Online at stacks.iop.org/ERL/8/034033

Abstract
While the international community aims to limit global warming to below 2 °C to prevent dangerous climate change, little progress has been made towards a global climate agreement to implement the emissions reductions required to reach this target. We use an integrated energy–economy–climate modeling system to examine how a further delay of cooperative action and technology availability affect climate mitigation challenges. With comprehensive emissions reductions starting after 2015 and full technology availability we estimate that maximum 21st century warming may still be limited below 2 °C with a likely probability and at moderate economic impacts. Achievable temperature targets rise by up to ∼0.4 °C if the implementation of comprehensive climate policies is delayed by another 15 years, chiefly because of transitional economic impacts. If carbon capture and storage (CCS) is unavailable, the lower limit of achievable targets rises by up to ∼0.3 °C. Our results show that progress in international climate negotiations within this decade is imperative to keep the 2 °C target within reach.

Keywords: climate change mitigation, 2 °C target, delayed climate policy, low-carbon technologies

S Online supplementary data available from stacks.iop.org/ERL/8/034033/mmedia

1. Introduction

Climate change is a major global challenge (IPCC 2007). The ultimate goal stated in the United Nations Framework Convention on Climate Change is to 'prevent dangerous anthropogenic interference with the climate system' (UNFCCC 1992). The international community adopted the long-term target of limiting the increase of global mean temperature to no more than 2 °C relative to pre-industrial levels. However, progress in the implementation of concrete emissions reduction policies has been slow. Even with the implementation of climate policy measures in several world regions, global emissions have continued to rise (Peters *et al* 2013, JRC/PBL 2012). Reaching the 2 °C target with high likelihood implies a tight limit on cumulative future anthropogenic greenhouse gas (GHG) emissions (Meinshausen *et al* 2009). Various reports have concluded that pledged national 2020 reduction targets fall short of the reductions required to meet the 2 °C target in a cost-optimal way (Höhne *et al* 2012, Rogelj *et al* 2010).

The decarbonization of economies requires a massive transformation in the way energy is produced and used (Fisher *et al* 2007, GEA 2012). Currently, the deployment of many low-carbon technologies faces technological difficulties or limited political support. For instance, carbon capture and storage (CCS), large-scale bioenergy production and nuclear energy are subject to sustainability concerns and public opposition. Similarly, integrating major shares of wind and solar power is challenging because of fluctuating supply from these sources.

In the past most climate mitigation scenarios were prepared under the idealistic assumptions of full flexibility in technology choice, globally coordinated climate policies ensuring that emission abatement would occur where it is cheapest, and the immediate start of climate policies (Fisher *et al* 2007, Knopf *et al* 2011). Meanwhile, several studies have considered climate mitigation scenarios with restricted technology portfolios (Edenhofer *et al* 2010, Azar *et al* 2010, Tavoni *et al* 2012), while others have investigated climate stabilization after a period of fragmented and delayed climate policy (Clarke *et al* 2009, Luderer *et al* 2012a, Jakob *et al* 2012, van Vliet *et al* 2012, IEA 2009). These studies showed that both technology availability and fragmented climate policy have a strong effect on the cost and achievability of climate targets. Only a few studies have analyzed the combined effects of delayed action and technology failure (Rogelj *et al* 2013a, 2013b, van Vliet *et al* 2012).

This study fills crucial research gaps. Currently available studies have almost exclusively used inter-temporally aggregated mitigation costs and carbon prices as indicators of mitigation effort. However, policymakers are much more concerned about the shorter term effects and distributional impacts of mitigation policies. Our work quantifies the trade-offs between the stringency of long-term climate targets on the one hand, and policy-relevant socio-economic challenges such as transitory costs, short-term energy price increases, and the potential redistribution of wealth induced by a global cap-and-trade regime on the other. By analyzing the impact of climate policy frameworks on these economic mitigation challenges, we examine how a further delay of global action forecloses long-term stabilization levels and technology choices.

2. Methods

We used the integrated energy–economy–climate model REMIND to produce a large ensemble of 285 scenario experiments, which combine different assumptions on (a) technology availability, (b) the start date of comprehensive global climate policies, and (c) globally harmonized carbon price levels.

2.1. Modeling framework

REMIND is an inter-temporal general equilibrium model of the macro-economy with a technology-rich representation of the energy system (Leimbach *et al* 2009, Bauer *et al* 2012, Luderer *et al* 2012b). It represents capacity stocks of more than 50 conventional and low-carbon energy conversion technologies, including technologies for generating negative emissions by combining bioenergy use with carbon capture and storage (BECCS). REMIND accounts for relevant path-dependencies, such as the build-up of long-lived capital stocks, as well as learning-by-doing effects and inertias in the up-scaling in innovative technologies. These path-dependencies are of particular importance for the study of energy transformation pathways in general and delayed action scenarios like the ones considered here in particular. REMIND represents 11 world regions, and operates in time-steps of five years in 2005–2060, and ten years for the rest of the century.

To examine the carbon cycle and climate system response to emissions, we employ a probabilistic setup of the reduced complexity climate model MAGICC (Wigley and Raper 2001, Meinshausen *et al* 2009, 2011). A detailed description of the modeling framework is available in the supplementary information (SI) section 1 (available at stacks.iop.org/ERL/8/034033/mmedia).

There are important caveats to the use of an economic model for the analysis of global, long-term mitigation pathways. For instance, the societal choices and behavioral patterns that drive energy supply and demand can be, unlike physical laws, subject to change and are therefore inherently difficult to predict (Koomey 2002). Similarly, the development and performance of energy supply technologies is highly uncertain. Our analysis should therefore not be mistaken for a *prediction* of future developments, but rather a strategic exploration of climate policy options based on a set of mitigation *scenarios*. As described in section 2.2, we use a large number of scenarios with different technology and policy assumptions to cover a wide spectrum of plausible climate futures.

2.2. Scenario definition

Along the policy-timing dimension, we consider three scenarios *Frag2015, Frag2020* and *Frag2030* with delayed adoption of cooperative mitigation action with globally harmonized GHG pricing resulting in comprehensive emissions reductions, assuming that climate policies remain weak and fragmented until 2015, 2020 and 2030 (cf figure 3(a)), respectively. In the time-steps before the start of cooperative action, world regions are assumed to follow a weak, fragmented climate policy regime based on a weak interpretation of the pledges or reduction proposals under the Cancun Agreements or Copenhagen Accord for 2020, and an extrapolation of the implied climate policy ambition beyond 2020 (*WeakPol* reference scenario, see SI section 6 (available at stacks.iop.org/ERL/8/034033/mmedia) and Luderer *et al* 2013). The *WeakPol* scenario yields similar global emissions by 2020 as the full implementation of the unconditional pledges under lenient accounting rules (UNEP 2012). While *Frag2015* marks an optimistic possible outcome of the current climate negotiations with a 2015 climate agreement resulting in enhanced reductions in 2020, *Frag2030* is a possible outcome of a failure of the current round of climate negotiations, with a continuation of weak and fragmented climate policies until 2030. In addition, we consider a (hypothetical) *immediate*, scenario with global comprehensive emissions reductions effective and implemented from 2015 onwards.

Along the scenario dimension of technology availability, we consider seven alternative cases, similar to those used in Kriegler *et al* (2013): (i) *default*—full technology portfolio, (ii) *NoCCS*—unavailability of CCS, (iii) *NoBECCS*—unavailability of CCS in combination with bioenergy (BECCS), (iv) *LimBio*—reduced bioenergy potential (100 EJ compared to 300 EJ in all other cases), (v) *NucPO*—phase out of investments into nuclear energy, (vi) *LimSW* —penetration of solar and wind power limited to 20%, and (vii) *LowEI*—lower energy intensity, with final energy demand per economic output decreasing faster than historically observed.

For each combination of technology and climate policy assumptions, we ran ten scenarios covering a wide spectrum of globally harmonized CO_2 price levels adopted after the start of comprehensive climate policies[5]. Globally harmonized CO_2 prices increase at 5% p.a., resulting in near cost-optimal inter-temporal emissions reductions to achieve a given long-term climate target (see SI section 5 for a discussion of the sensitivity of results to climate policy formulation available at stacks.iop.org/ERL/8/034033/mmedia). These scenarios yield a wide range of responses in the economy and the climate system. In addition, we performed some scenario experiments with a prescribed cumulative 2010–2100 GHG budget. They allow contrasting results from different scenarios with comparable climate outcomes. A more detailed description of the scenario setup is provided in SI section 2 (available at stacks.iop.org/ERL/8/034033/mmedia).

2.3. Economic indicators of mitigation challenge

We use four economic indicators to capture the breadth of economic and institutional challenges of stringent climate policies, and their dependence on the timing of climate policies and technology availability. (i) *Aggregated mitigation costs* are a commonly used proxy indicator of the long-term effects of climate policies. We define them here as macro-economic consumption losses aggregated with a discount rate of 5% over the time horizon 2010–2100, relative to aggregated and discounted gross world product (GWP). In addition, we use (ii) *transitional growth reduction*, defined as the maximum reduction of decadal consumption growth induced by climate policies in percentage points (pp) as a proxy of potential short-term disruptions during the phase-in of climate policies; (iii) *carbon market value*, defined as the aggregated and discounted value of greenhouse gases emitted from 2010–2100, as a proxy for the potential distributional conflicts when defining the regional and sectoral burden sharing under a comprehensive cap-and-trade regime; and (iv) the short-term *energy price increase* induced by climate policies, measured in terms of an aggregated global final energy price index, as a proxy for the effect of climate policies on the energy bills of households and firms. These indicators allow us to assess not only the long-term mitigation challenges, but also the challenges encountered at time-scales that are more relevant for today's decision-makers. SI section 3 (available at stacks.iop.org/ERL/8/034033/mmedia) provides the technical details on these indicators, and the rationale behind the parameter ranges chosen. Note that these economic indicators only measure efforts related to emissions reductions, but do not account for avoided damages or co-benefits of climate change mitigation.

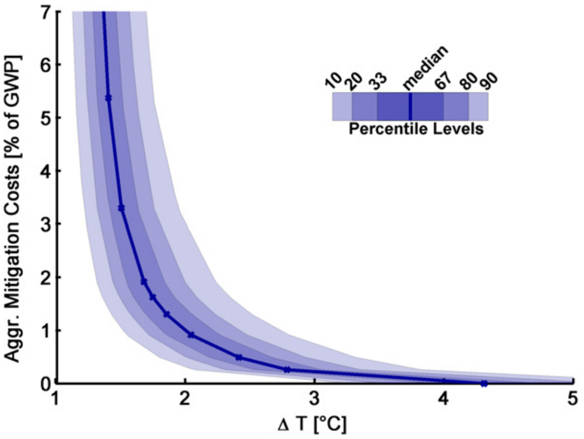

Figure 1. The 'achievability frontier' describing the trade-off between maximum 21st century surface air temperature increase and aggregated mitigation costs for the *Frag2015* scenario with *default* technology assumptions. Shaded bands show uncertainty ranges of the climate system's response to anthropogenic activities.

3. Results

3.1. Temperature-cost-trade-off curves

Relating mitigation to maximal temperature increase until 2100 establishes temperature-cost-trade-off curves, as shown in figure 1. The lower the maximal temperature over the 21st century, the higher the inter-temporally aggregated mitigation costs as a share of GWP. This property gives rise to the notion of an economic achievability frontier, i.e., a lower limit of achievable climate targets for a given macro-economic cost level. The temperature-cost-trade-off curves are highly convex, i.e., costs increase disproportionally with the increasing stringency of the long-term temperature target.

The climate system's response to anthropogenic emissions is subject to substantial uncertainties, which we address explicitly. In the *Frag2015* scenario with *default* technology assumptions, limiting global warming to below 2 °C with a 50% likelihood (ΔT_{50}) results in long-term mitigation costs of around 1.0% of GWP. Reaching the target with a likelihood of two-thirds (ΔT_{67}) implies long-term costs of 1.4%. We find a very tight, approximately linear relationship $\Delta T_{50} = 0.901\Delta T_{67} + 0.021\,°\mathrm{C}$ (cf figure S5 available at stacks.iop.org/ERL/8/034033/mmedia), based on which these two confidence levels can be easily converted into each other.

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[5] CO_2 prices exhibit strong regional differences in the *Frag2015, Frag2020* and *Frag2030* scenarios until 2015, 2020 and 2030 respectively, and converge to the globally harmonized level thereafter.

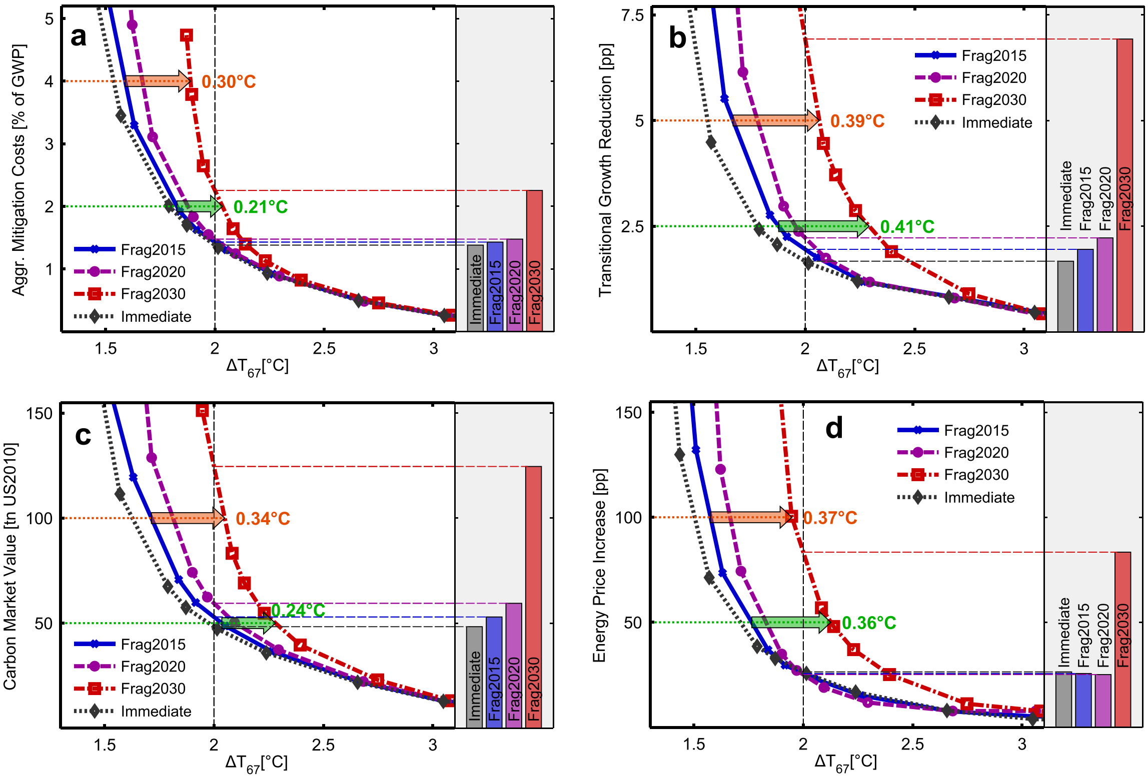

Figure 2. Temperature-cost-trade-off curves showing the effect of timing of global comprehensive mitigation action on (a) aggregated mitigation costs, (b) transitional consumption growth reductions, (c) carbon market value, and (d) energy price increase (*default* technology assumptions). *X*-axis shows temperature targets (maximum 2010–2100 temperatures) reached with a 67% likelihood. Bar charts indicate economic challenge of limiting warming to 2 °C.

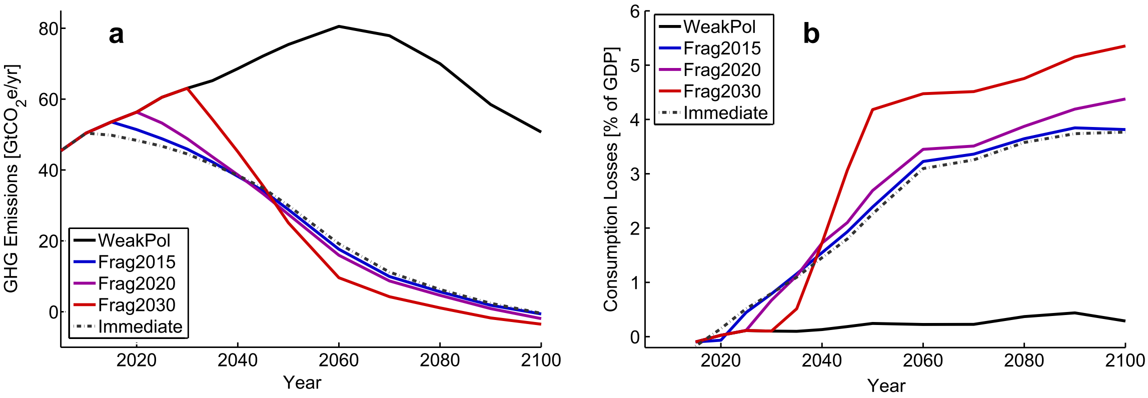

Figure 3. (a) Emission pathways and (b) consumptions losses for the reference scenario with weak polices (WeakPol), as well as for stabilization scenarios with a cumulative emissions budget of 2500 $GtCO_2e$, with immediate (immediate) or delayed implementation of comprehensive emissions reductions (*Frag2015, Frag2020, Frag2030*).

In the remainder of this letter, temperature targets refer to levels achieved with 67% likelihood.

3.2. Effect of delayed action

For all economic mitigation challenge indicators, a further deferral of comprehensive global emissions reductions results in a shift of the temperature-cost-trade-off curves towards higher costs and higher temperatures (figure 2). Thus, a delay of comprehensive climate policies implies not only higher costs for reaching a given climate target (bar charts), but also an increase of the lower level of climate targets achievable within the range of acceptable cost levels, as indicated by the arrows in the figure. For climate targets around 2 °C, the effects of delay on inter-temporally aggregated costs are substantial. This is in spite of the fact that lower costs in the short-term partially offset the higher long-term costs, which are subject to greater discounting (figure 3(b))[6].

[6] Since mitigation costs as a share of GWP increase over time, aggregated mitigation costs depend on the discount rate used for the inter-temporal aggregation. The sensitivity studies shown in SI section 4 (available at stacks.iop.org/ERL/8/034033/mmedia) demonstrate that lower discount rates result in higher mitigation costs and stronger effects of delayed action, but do not change the qualitative conclusions of the analysis.

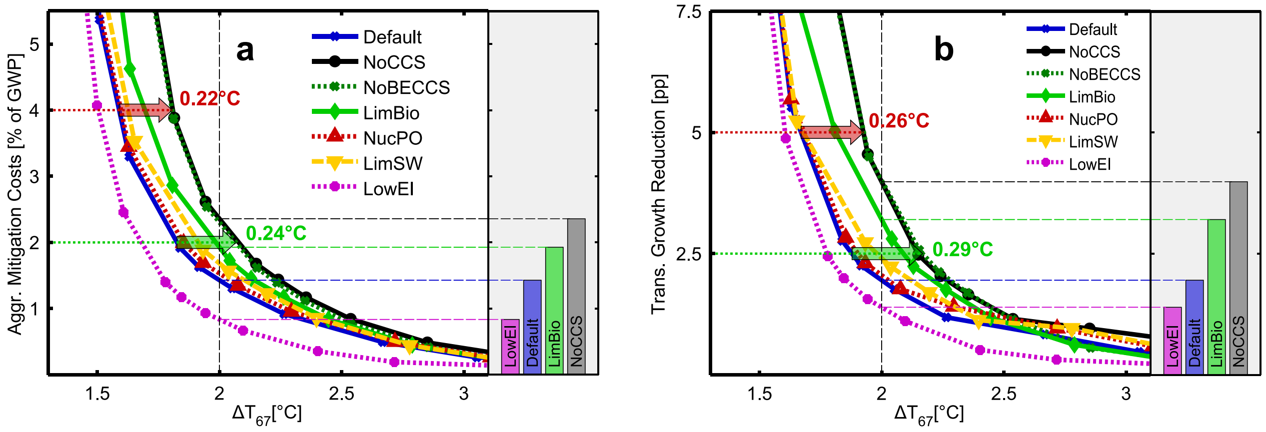

Figure 4. Temperature-cost-trade-off curves showing the effect of technology availability on (a) aggregated mitigation costs, and (b) transitional growth reduction (*Frag2015* scenario). Temperature targets (maximum 2010–2100 temperatures) reached with a 67% likelihood. Bar charts indicate economic challenges of limiting warming to 2 °C.

The longer the climate policy regime remains weak and fragmented, the higher are the emissions reduction rates required after the implementation of comprehensive climate policies to reach low stabilization targets (figure 3(a), see also Stocker 2012). This is mirrored in the development of policy costs measured in terms of consumption losses over time, which show an abrupt increase of costs in case of cooperative action delayed beyond 2030 (figure 3(b)). The effect of delay on the transitional growth reduction after implementation of comprehensive emissions reductions is therefore even more pronounced than the effect on aggregated mitigation costs. For aggregated mitigation costs in the range of 2–4% of GWP, lowest achievable climate targets in *Frag2030* exceed those found for *Frag2015* by 0.2–0.3 °C. For transitional mitigation costs in the range of 2.5–5 pp, the shift even amounts to ∼0.4 °C. Recent macro-economic data suggest that a short-term growth reduction of 5 pp is comparable to the effect of the financial crisis (IMF 2012). We also find that transitional costs for limiting warming to 2 °C is three times higher in case of *Frag2030* than in *Frag2015*.

The impact of mitigation timing on short-term energy price increases is similar to that on the transitional growth reductions. Lowest climate targets achievable at energy price increases of 50–100 pp shift by almost 0.4 °C if climate policies remain weak and fragmented until 2030 (figure 2(d)). Increases of final energy prices in comparable magnitude have been observed in the past for individual regions or energy carriers (see SI section 3 available at stacks.iop.org/ERL/8/034033/mmedia). In case of full technology availability, the short-term energy price increase induced by climate policies consistent with 2 °C stabilization remains moderate at around 25 pp even in the *Frag2020* scenario, but more than thrice this value in *Frag2030*.

Carbon pricing—which ensures economic efficiency (Fisher *et al* 1996)—emerges as a crucial institutional challenge. If the 2 °C target is implemented in the *Frag2015* scenario, the cumulated present value of emissions permits in 2010–2100 amounts to US$ ∼50 trillion, which is comparable to the market value of crude oil consumed over the same period in the baseline scenario without climate policy. If action is delayed beyond 2030, the carbon market value implied by 2 °C stabilization more than doubles, and lowest climate targets achievable at cumulated carbon market values of US$ 50–100 trillion shift by ∼0.3 °C.

3.3. Effect of technology availability

We focus the further discussion on aggregated mitigation costs and transitional growth reduction (figures 4 and 5). Insights for carbon market value and energy price increases are qualitatively similar and shown in figures S2 and S7 (available at stacks.iop.org/ERL/8/034033/mmedia). We observe that the availability of CCS technologies has a strong influence on target achievability. Lowest achievable mitigation targets increase by 0.2–0.3 °C if CCS cannot be used. Limited bioenergy potential also results in a significant shift in the temperature-cost-trade-off curves. The similarity of the results of (a) unavailability of BECCS and (b) unavailability of both BECCS and fossil CCS underscores the importance of negative emissions, and suggests that BECCS is more crucial for low stabilization than fossil CCS. A variety of alternative low-carbon options for electricity production is available; therefore, limitations on nuclear or wind and solar power have relatively small economic effects. By contrast, if economies increase their energy efficiency at a higher rate than has been historically observed, costs for reaching the 2 °C target decrease by 40%, and even lower climate targets become achievable already at moderate costs.

3.4. Targets achieved with temporary temperature overshoot

So far, we focused on climate outcomes in terms of maximal temperature increases over the 21st century. This is equivalent to formulating climate targets as not-to-exceed. Alternatively, 2100 temperature levels can be considered, equivalent to allowing for temporary overshooting of the long-term climate target. For the high end of mitigation cost levels, and if biomass and CCS are available, we observe that in terms

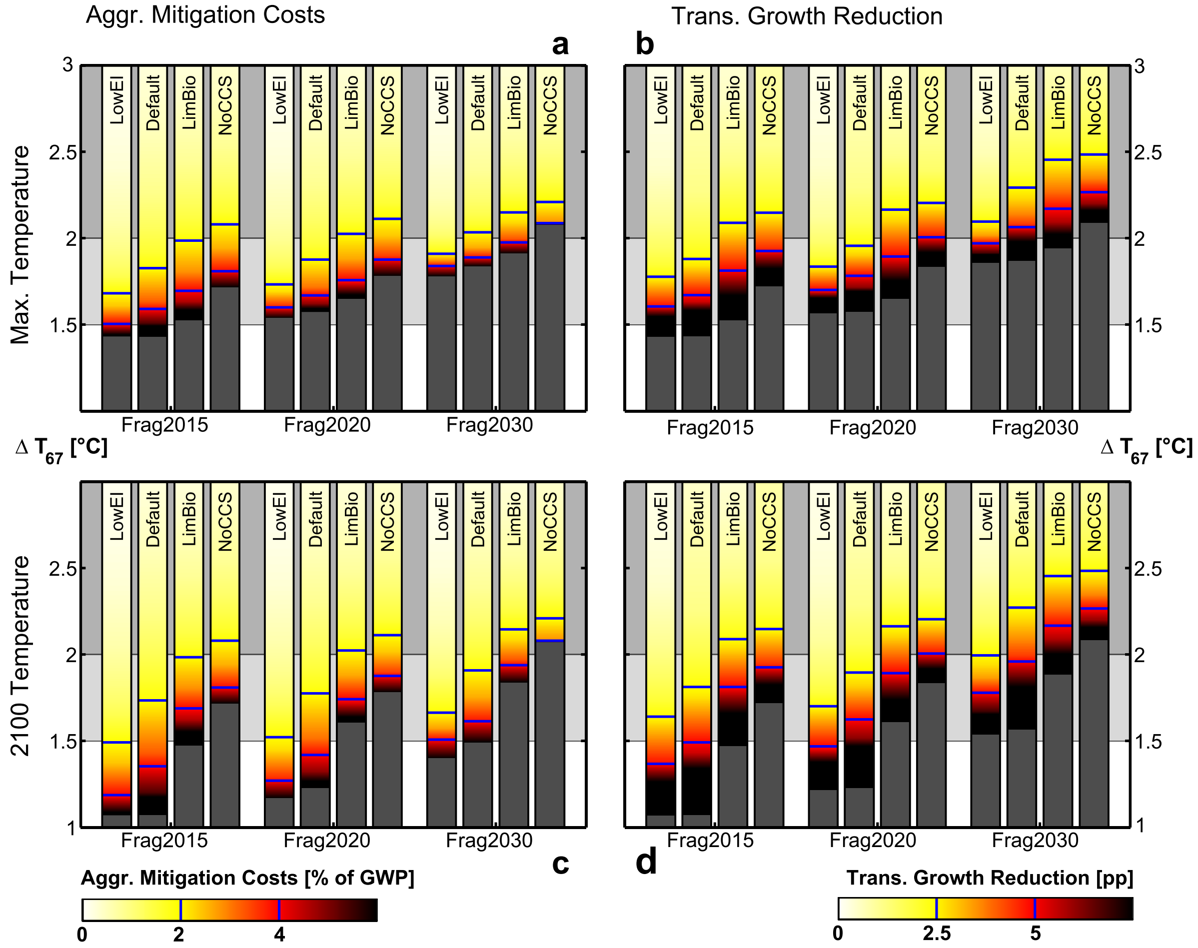

Figure 5. Overview of the combined effects of mitigation timing and technology availability on achievability of either not-to-exceed targets (in terms of maximum 2010–2100 temperature increase, upper panels), or 2100 temperature targets that allow for temporary overshoot (lower panels). Graphs show economic challenges (color shading) in terms of aggregated policy costs (left panels (a), (c)), and transitional growth reduction (right panels (b), (d)), as a function of temperature targets reached with 67% likelihood. Dark gray areas at the base of bars indicate temperature target levels that were not achieved with the range of carbon price paths assumed.

of 2100 temperatures considerably lower climate targets can become achievable than in terms of maximal 2000–2100 temperatures (figures 5 and S7, S8 available at stacks.iop.org/ERL/8/034033/mmedia). In the *Frag2015* scenario with default technology assumptions, 2100 temperatures achievable with 67% likelihood at aggregated costs of 4% of GWP drop to 1.35 °C, compared to 1.6 °C in terms of maximum 2000–2100 temperatures. The results also show that technology availability has a greater influence on lowest achievable 2100 temperature levels than on maximum 21st century temperatures (figure S6 available at stacks.iop.org/ERL/8/034033/mmedia). This is because for trajectories with overshoot, the effects of technologies only come to bear in a limited time frame (until the maximum temperature is reached), while in case of 2100 temperatures the effects of technology cumulate over the entire century. This is particularly relevant for bioenergy and CCS, which are ramped up relatively slowly in the 1st half of the century, but become very significant after 2050, if the technologies are available.

4. Discussion and conclusions

In view of the slow progress of international climate negotiations and emissions reduction efforts, the political achievability, and the technological and economic implications of limiting global warming to 2 °C are debated controversially. Model-based scenarios of climate change mitigation pathways are crucial tools for assessing the implications of alternative policy choices. Our work maps out the trade-offs between the stringency of climate targets and economic mitigation challenges at a very high level of detail. It shows how a continuation of ineffective climate policies reduces the option space for future climate policy, increasing mitigation challenges and the reliance on technologies for removing CO_2 from the atmosphere.

Under optimistic assumptions about the outcome of current climate negotiations and technology availability, we estimate that economic mitigation challenges become prohibitively high for temperature stabilization targets below ~1.7 °C. This means that much of the room to accommodate the 2 °C target has already been consumed. The results suggest that delaying comprehensive emission reductions by another 15 years pushes this target out of reach. In case of technology limitations, the urgency of reaching a global climate agreement is even higher.

A continuation of weak climate policies inevitably increases the risk of exceeding the 2 °C threshold. Returning to 2 °C in such a scenario will be difficult, and requires large-scale deployment of BECCS. We find that temperature levels reached in 2100 depend to a much higher extent than maximum 2010–2100 temperatures on the availability of technologies, with unavailability of CCS reducing achievable target levels by almost 0.5 °C.

Our research also demonstrates that the effects on short-term consumption growth and energy prices as well as the redistribution of wealth induced by CO_2 pricing are crucial challenges of mitigation pathways consistent with 2 °C. This finding points to potentially strong distributional effects of climate policies, which increase strongly if comprehensive climate policies are delayed further. Additional work is needed to analyze policy instruments and institutional requirements to address these challenges.

The results have important implications for climate policy. They show clear trade-offs between long-term climate targets and economic mitigation challenges. They also demonstrate that these trade-offs depend strongly on the start date of substantial emissions reductions and technology availability. The longer the international community delays the implementation of comprehensive climate policies, the more critical these trade-offs will be.

Acknowledgments

We thank Jan Minx, Nico Bauer, Michael Jakob and Niklas Hoehne for helpful discussions, and Michaja Pehl for his assistance in the data processing. Research for this publication was supported by the German Federal Environment Agency (UBA) under UFOPLAN FKZ 3710 41 135.

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