Economic Mitigation Challenges: How Further Delay Closes the Door for Climate Targets

– Policy Brief –

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September 2013

1 Motivation and background

Climate change is broadly recognized as one of the major global challenges humanity is facing (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". In the Copenhagen Accord and the subsequent Cancun Agreements, 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. While no level of global warming can be considered inherently safe, stabilization of climate change at 2°C above pre-industrial levels may substantially reduce the risk of large-scale discontinuities, for instance the melting of the Greenland ice sheet (Lenton et al. 2008; Smith et al. 2009). Despite the broad recognition of the 2°C target, progress in the implementation of concrete emissions reduction policies has been slow. Even with the implementation of climate policy measures in several world regions (UNEP 2012), global emissions have continued to rise (EDGAR 2011). Reaching the 2°C target with a likely chance implies a tight limit on cumulative future anthropogenic greenhouse gas (GHG) emissions (Meinshausen et al. 2009; Matthews 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 (UNEP 2010, 2011, 2012; Rogelj et al. 2010).

CO_2 emissions have a long-lasting effect on the climate system. To achieve climate stabilization by halting and eventually reversing the increase in atmospheric GHG concentrations, global GHG emissions must be reduced to near zero in the long run (Matthews and Caldeira 2008). This implies the need for a comprehensive global regulation of GHG emissions that covers all regions and sectors. Offsetting the remaining emissions requires mitigation options that result in net-negative emissions – such as carbon sinks in forestry or the combination of bioenergy use and carbon capture and storage (BECCS). The decarbonization of economies requires a massive transformation in the way energy is produced and used. No single technology option is sufficient for this task. Currently, however, the deployment of a substantial portfolio of low-carbon technologies faces technical difficulties or limited political support. For instance, carbon capture and storage (CCS), large scale bioenergy production, or 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.

Against this background, an in-depth analysis of the achievability of the 2°C target is timely. Through a model-based scenario analysis, we addressed the following research questions:

- What are key requirements and implications of transformation pathways consistent with the 2°C target?
- How do further delays in comprehensive global climate policies affect the attainability of the 2°C target?
- How does the availability of technology options influence the costs of climate stabilization?

This policy brief summarizes the key results that have emerged from the study. The results are presented in detail in the research article "Economic mitigation challenges – how further delay closes the door for achieving climate targets" (Luderer et al. 2013b), published in the Environmental .

2 Study design

To study the technological, institutional and economic requirements of meeting the 2°C target, we used the integrated energy-economy-climate model REMIND in combination with the probabilistic climate model MAGICC to and evaluated a wide range of scenarios combining different assumptions regarding the start date of comprehensive global climate policies and technology availability.

International climate policy

We compared the following three international climate policy scenarios, which differ in terms of start dates of comprehensive global climate action toward the 2°C target. They represent a wide range of possible outcomes of the currently on-going negotiations of the Durban Platform:

I. *Frag2015* –an optimistic case assuming that the on-going Durban Platform negotiations result in an agreement by 2015 that replaces the fragmented state of international climate policies with a global comprehensive emission reductions starting in 2020
II. *Frag2020* – assuming that the Durban Platform fails to enhance emission reduction pledges for 2020, but yields a binding agreement on comprehensive emission reductions starting in 2025
III. *Frag2030* – assuming a failure of the Durban Platform negotiations resulting in a further continuation of fragmented climate policies until 2030 and a delay of comprehensive emissions reductions until 2035

In any of these cases, we assume that the global climate policy regime is preceded by a period during which different nations pursue moderate carbon reduction and energy policy ambitions in line with a weak interpretation of the Copenhagen Pledges and their extension into the future. In addition, we consider a scenario in which we assume immediate action, i.e. comprehensive emissions reductions starting already in 2015 *(Immediate)*. This scenario must be considered hypothetical, since none of the current climate negotiation tracks would be able to deliver such an outcome. Any of these scenarios is modeled through the end of the 21st century.

Technology availability

We combine the policy cases with six variants of technology availability:

I. Default – full technology portfolio
II. NoCCS – no availability of carbon capture and storage (CCS)
III. NoBECCS – no availability of bioenergy with carbon capture and storage (BECCS)
IV. LimBio – reduced bioenergy potential (100 EJ compared to 300 EJ in all other cases)
V. NucPO – phase-out of nuclear energy
VI. LimSW – penetration of solar and wind power limited to 20%
VII. LowEI – lower energy intensity, with final energy demand per economic output decreasing faster than historically observed

Economic indicators of mitigation challenges

To evaluate how these policy and technology cases impact the economic achievability of meeting climate targets, we examine the following indicators:

I. *Aggregated mitigation costs*, calculated as macro-economic consumption losses relative to the gross world product (GWP) in the baseline scenario; both consumption losses and GWP are aggregated over the time horizon 2010-2100 and discounted at 5%;
II. *Transitional growth reduction* – calculated as the reduction of income growth during the first decade after the phase-in of comprehensive mitigation policies and used as an indicator of the short-term distortions induced by the phase-in of climate policies;
III. *Carbon market value*, defined as the aggregated and discounted value of greenhouse gases emitted from 2010–2100, used as a proxy for the potential distributional impacts when defining the regional and sectoral burden sharing under a comprehensive cap-and-trade regime;
IV. *Energy price increase*, measured in terms of the climate-policy-induced short-term increase of the global final energy price index, as an indicator of 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. 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.

Modeling framework

Our analysis combines an ensemble of scenarios from the integrated energy-economy-climate model REMIND (Luderer et al. 2013a) with the climate model MAGICC (Meinshausen et al. 2011). REMIND is an intertemporal general equilibrium model of the macro-economy of 11 world regions. Investment decisions in REMIND are based on inter-temporal foresight, although in the climate policy scenarios of this study, future policy changes are not anticipated. REMIND represents capacity stocks of more than 50 conventional and low-carbon energy conversion technologies as well as global learning curves for non-mature technologies.

To examine the climate response to emissions, we employed a probabilistic setup of the reduced complexity climate model MAGICC in a version that includes permafrost feedbacks. We constrained the parameter space so that the marginal climate sensitivity distribution closely represents the IPCC Fourth Assessment Report conclusions regarding our uncertainty about climate sensitivity. The analysis considers all important greenhouse gases, tropospheric ozone precursors, the direct and indirect aerosol effects and land-use albedo.

3 Key Results

We analyze the achievability of the 2°C target under different climate policy frameworks and technology assumptions based on the various economic challenge indicators specified in section 1.1.3.

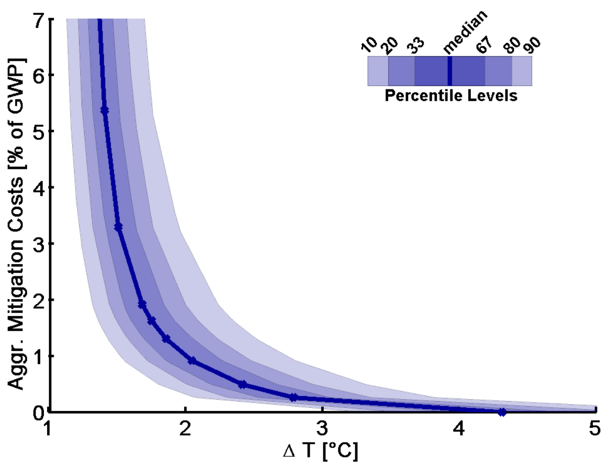
Our results show how a continuation of ineffective climate policies reduces the option space for future climate policy, increasing mitigation challenges and the reliance on technologies for removing CO_2 from the atmosphere. Under optimistic assumptions about the outcome of current climate negotiations 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. In the following, we present specific findings in detail.

(1) The 2°C target can still be met, but there is not much leeway

Our modeling indicates that it is technically and economically feasible for the international community to sufficiently restrain atmospheric GHG concentrations so that global warming can likely be limited to 2°C above preindustrial levels. However, this conclusion is very sensitive to assumptions about the timing and effectiveness of policies, the availability of mitigation technology options, and the climate system's response. Mitigation costs rise dramatically if the target stringency is beyond the reach of affordable mitigation options. A robust finding from our modeling is that for any given set of policy and technology assumptions, there is such a point beyond which mitigation costs increase disproportionately. We find that under favorable circumstances, the 2°C target is not yet beyond such a point but that there is limited leeway for inefficient climate policies. Effective international cooperation and a broad portfolio of mitigation options are needed as otherwise the potential for affordable mitigation could fall short of the 2°C target.

The lack of leeway for achieving the 2°C target is illustrated in Figure 1. Based on our modeling, this figure shows the relation between temperature increases and mitigation costs, assuming a global climate policy regime is agreed upon in 2015 and results in emissions reductions consistent with the long-term target by 2020 as well as a default range of technology options. The aggregate mitigation costs of limiting global warming to 2°C with 67% likelihood[1] are shown to be below 1.5% of gross world product. Even moderately more stringent targets, however, can increase the costs substantially. If circumstances are less favorable than assumed in this figure – e.g. policy delays, inefficient implementation, or technology barriers – the curve would move to the right, and the upsurge in mitigation costs would already occur around the 2°C target. The room for delay and technology choices is therefore limited, as elaborated in the next sections.

Figure 1 : The tradeoff between 21st century surface air temperature (maximum increase during 2010-2100 relative to pre-industrial levels) and aggregated mitigation costs for the *Frag2015* scenario with Default technology assumptions. Shaded bands show geophysical uncertainty ranges.



(2) 2°C requires a full-scale transformation of global energy systems

Climate stabilization requires a full-scale transformation of the global energy system to low-carbon technologies. In order to meet the 2°C target with a likely chance, global GHG emissions roughly have to be cut in half relative to current levels by about mid-century and approach zero toward the end of the century. In case of any substantial delay in global cooperation on climate policy, a 2°C target may even require net-negative global GHG emissions by the end of the century in order to offset excess atmospheric concentrations of greenhouse gases due to the failure to regulate emissions effectively in the near term.

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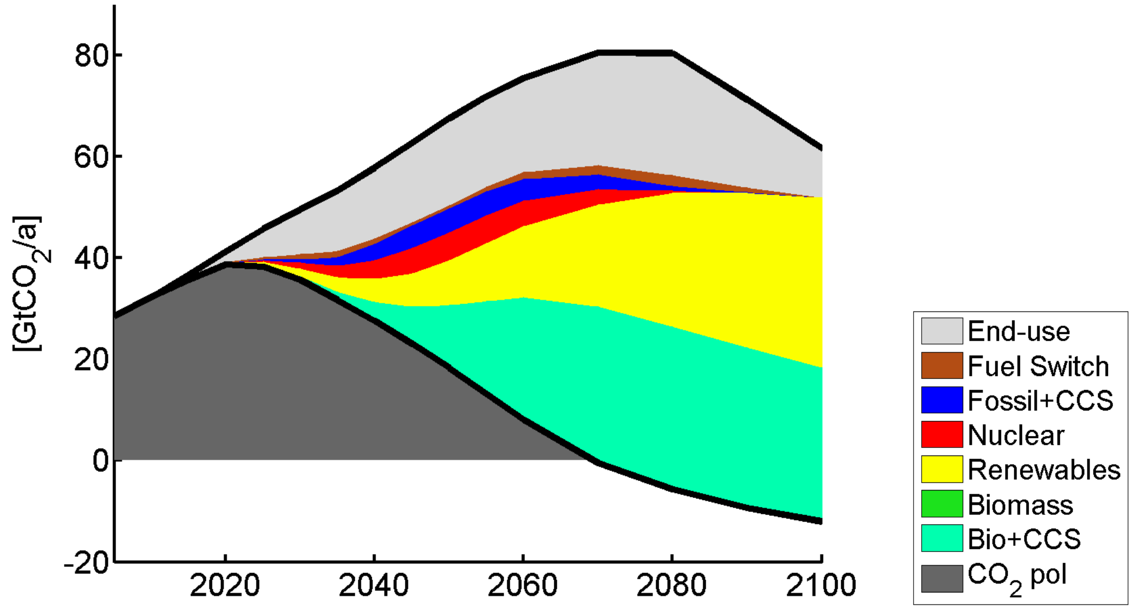
[1] The 67% likelihood level corresponds to a "likely" chance in IPCC terminology. It will be used as a reference point throughout this report.

Figure 2: Contribution of technologies to the reduction of CO_2 emissions from the energy system.

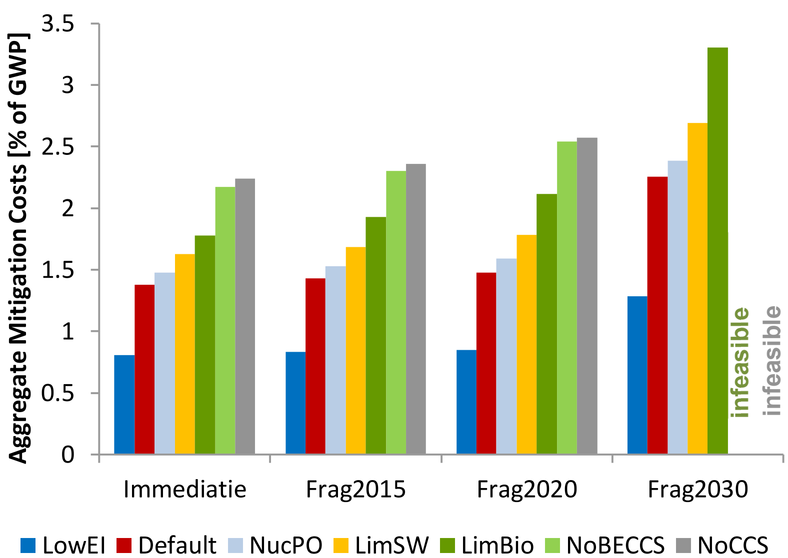


No single technology is sufficient to deliver such dramatic emissions reductions. Rather, a portfolio of options is needed. Figure 2 shows how different technology groups contribute to emissions reductions for a 2°C scenario that assumes full technology availability. The costs for reaching the 2°C target with a likely chance is a function of technology availability and the delay of a comprehensive global agreement, as shown in Figure 3. We observe that the impact of foregoing technology options depends on technology types. Unavailability of both fossil CCS and BECCS results in the greatest increase in the costs of mitigation. 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 suggest that BECCS is more crucial for low stabilization than fossil CCS. Limited bioenergy availability also increases the costs of mitigation substantially. In case of a nuclear phase-out, mitigation costs are only slightly higher than in the scenario with full technology availability. Limited deployment of solar and wind power has a relatively moderate impact on costs.

The results can be understood in terms of a principle difference between decarbonization patterns of electricity and non-electric energy supply. For power generation, a variety of alternative low-carbon options is available, such as nuclear, solar and wind power, carbon capture and storage and bioenergy. Transitioning to these options requires clear policy signals that establish a solid basis for investments so that the reliance on current, carbon-intensive power systems can be overcome. In addition, the large-scale deployment of low-carbon power options faces technical and political hurdles such as the intermittency of solar and wind power and the risks of nuclear power. Nonetheless, viable solutions are being developed and even if the barriers to some of these options remain unresolved, there are enough alternatives for low-carbon electricity to make up for limitations among some options. Our modeling indicates that decarbonizing the global electricity sector is techno-economically feasible regardless of whether this transformation relies heavily on nuclear power or primarily on renewable energy.

While the electricity sector can be readily decarbonized, only few options exist to reduce emissions from non-electric energy use in industry, buildings and transport. These include energy efficiency improvements, the switch to electricity as an energy carrier (e.g. by an electrification of transport, or by using geothermal heat pumps in buildings), and the use of bioenergy. If global emissions are not curtailed fast enough, atmospheric GHG concentrations may reach levels that require any remaining emissions to be offset by negative emissions elsewhere. A primary means for achieving this is bioenergy in combination with carbon capture and storage (BECCS), which stores in the ground the CO_2 extracted from the atmosphere by energy crops. If BECCS is not an option because CCS technologies are unavailable, it becomes increasingly difficult to achieve the 2°C target even with a decarbonized electricity sector. The aggregated costs of achieving the 2°C target increases by about 65% if CCS is not available in our *Frag2015* scenario, in which a global climate agreement is reached in 2015, and by about 75% if the agreement is delayed until 2020 (Figure 3). If a global climate policy agreement is delayed until 2030, the 2°C can no longer be achieved without negative emissions through BECCS. Limited bioenergy potential also reduces the potential for BECCS and raises the cost of low climate stabilization. This outcome confirms the results of previous studies that have pointed out the crucial importance of BECCS for low stabilization despite the land use challenges that large-scale bioenergy use may entail (Edenhofer et al. 2010; Azar et al. 2010). Since nuclear, solar and wind power can be substituted for each other, the cost impacts of a nuclear phase-out or of limited potential for solar and wind energy are much more limited.

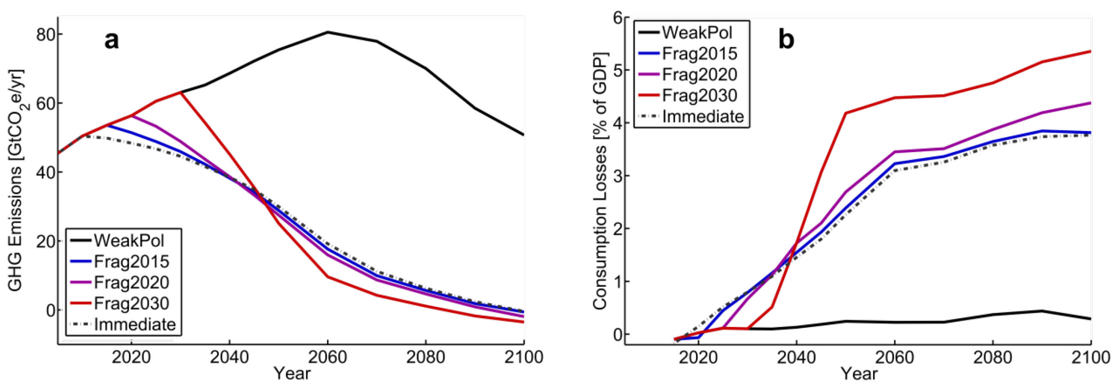
Figure 3: Mitigation costs as a share of gross world product (GWP), each aggregated over the 21st century and discounted at 5%, for the *Frag2015*, *Frag2020* and *Frag2030* policy cases and different technology cases: default technology availability (Default) nuclear phase-out (NucPO), limited potential for solar and wind energy (LimSW), limited bioenergy availability (LimBio), and unavailability of carbon capture and storage (NoCCS). If a global climate agreement is delayed until 2030, meeting the 2°C target is infeasible in the NoCCS case.



(3) A comprehensive global agreement on emission reductions needs to be implemented soon

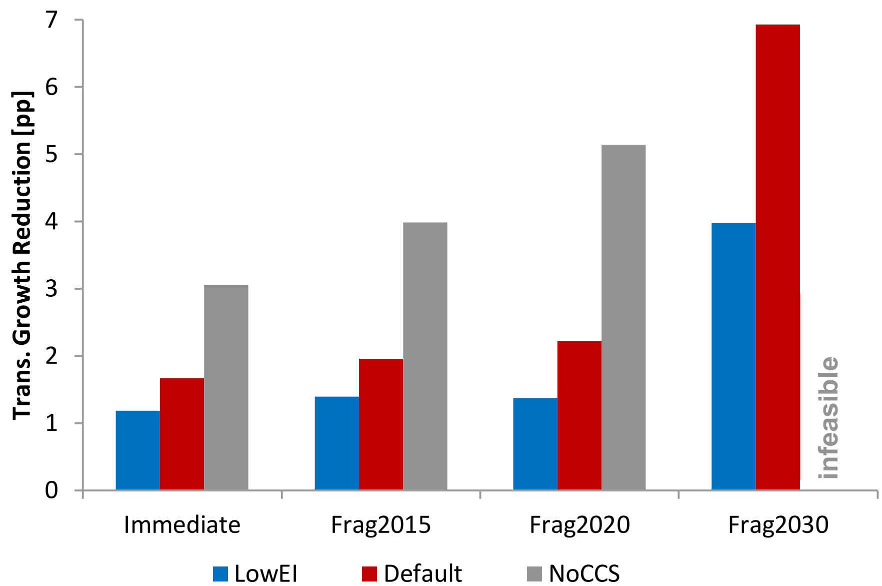
The stated goal of the ongoing Durban negotiations is to limit global warming to 2°C above preindustrial levels through a comprehensive global climate policy regime envisioned to be agreed upon in 2015 and to enter into force by 2020. Even if these aspirations are met, global GHG emissions would have to approach zero over the course of the century in order to prevent further temperature increase. Any delay of climate policies results not only in higher emissions in the short term, but also in fewer medium-term mitigation opportunities after the adoption of comprehensive emission reduction targets ("carbon lock-in"). The higher emissions have to be offset later by more rapid and deeper emission cuts in order to still reach the same climate stabilization target. (Figure 4a). The economic implications can be substantial, since delayed action necessitates the use of expensive mitigation options that could be avoided if emissions are cut earlier. Our modeling shows that delaying the implementation of a global climate policy regime increases aggregate mitigation costs, despite avoiding short-term costs and even if long-term costs are discounted at 5% per year (Figure 4b). Delayed action also increases the reliance on technologies that are not yet commercially available, or subject to sustainability concerns (see Point (6) below).

Figure 4: (a) Emission pathways, and (b) consumption losses for the Baseline scenario and for scenarios with continuation of fragmented climate policies until a global deal is struck in 2015 (*Frag2015*), 2020 (*Frag2020*), or 2030 (*Frag2030*).



Among the most challenging implications of a delayed policy regime are the inertia of energy systems and the economic distortions that a rapid transition would entail. A policy delay would allow further expansion of carbon-intensive capacity that would need to be retired before the end of its economic lifetime if climate objectives are to be achieved. In scenarios with a delay of a global agreement until 2030, transitioning to climate policies in line with the 2°C target would reduce global consumption growth by about 7 percentage points during the transition decade under default technology assumptions, compared to 2 percentage points in case of an agreement in 2015 that is implemented in 2020. Measured against global consumption growth in the baseline of around 30% to 40% per decade of the first half of the 21st century, such a dramatic short-term effect would render the political feasibility of delayed mitigation questionable. For comparison, IMF data suggests that the financial crisis of 2008 reduced global economic output by around 5%. Only particularly favorable energy efficiency policies would limit transitory global consumption growth reduction to around 5 percentage points if a stringent climate agreement is delayed until 2030. By contrast, if a comprehensive agreement is reached in 2015 and implemented by 2020, growth reduction during the transition decade can be kept below 2 percentage points in the default technology case.

Figure 5: Transitional growth reduction during the decade following the implementation of a global climate policy agreement made in 2015 (*Frag2015*), 2020 (*Frag2020*), or 2030 (*Frag2030*) under alternative technology assumptions: low energy intensity (LowEI), Default, and unavailability of CCS (NoCCS).



Our results also demonstrate that the reliance on uncertain and potentially unsustainable technologies is greatly increased if mitigation action is delayed further. In case of a further delay, the cost markup induced by technology failure increases substantially (Figure 3). For the *Frag2030* scenario, we even find that within the assumptions used in our model it is impossible to reduce emissions sufficiently fast for reaching the 2°C target with a likely chance if CCS is unavailable.

(4) Dedicated energy efficiency policies can increase the leeway in the climate mitigation effort

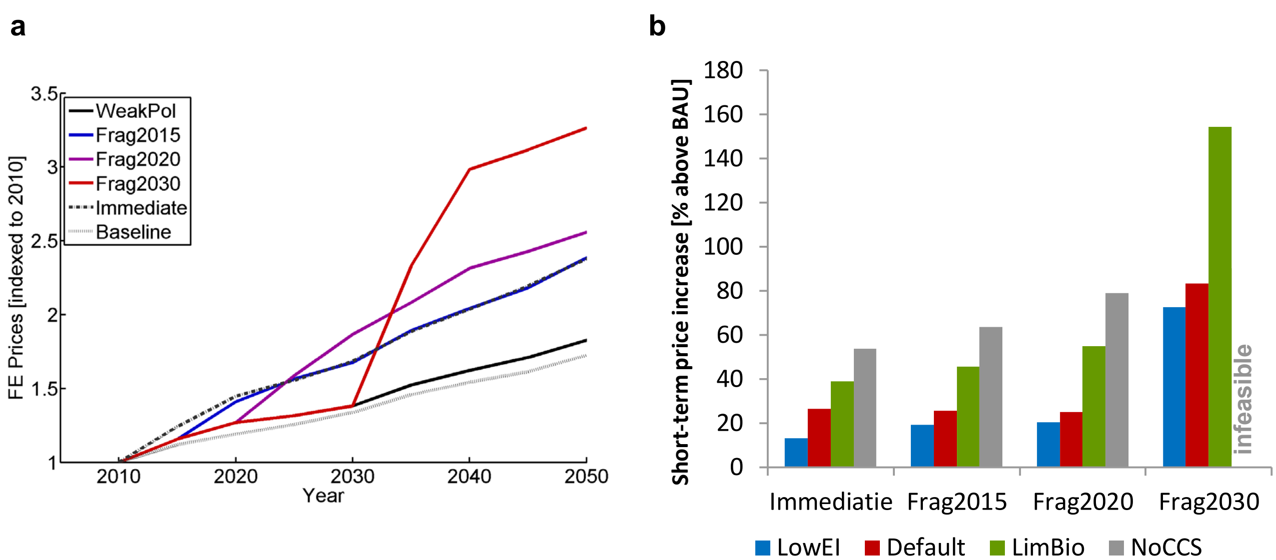
The implementation of carbon pricing leads to an increase in energy prices, and is therefore bound to increase the return on energy efficiency investment by increasing the value of energy savings. This mechanism of demand responses to increasing energy prices is taken into account in our default climate policy scenarios and is fully captured by the energy-economic modeling framework. However, due to market failures and implementation barriers, it is unlikely that carbon pricing alone is able to deliver the full cost-effective energy efficiency potential. Dedicated policies can help to remove barriers such as split incentives between landlords and residents, access to energy efficiency financing, and lacking information about appliance energy use. The energy intensity of economies can also substantially improve through behavioral changes that result in lower demand for final energy. Such behavior changes may not be directed but could be facilitated by policy.

When modeling a scenario under which the energy intensity of the global economy improves at a significantly faster than historical rate – resulting in a 25% lower energy intensity in 2050 than if historical trends continued – we observe that more leeway is created for affordable climate mitigation. For instance, the low-energy-intensity case reduces the transitional growth reduction during the first decade of comprehensive global climate policy by 29% if a global agreement is reached in 2015 and even by 38% or 43% respectively if the agreement is reached in 2020 or 2030 (Figure 5). Since transitional costs are among the main barriers to stringent policy implementation, improved energy efficiency can significantly improve the acceptance of ambitious climate policies. Our analysis does not combine the low-energy-intensity case with cases in which mitigation technologies are limited, but it stands to reason that improved energy efficiency can also offset some of the mitigation cost impact of limited low-carbon energy supply options.

(5) We need strong institutions to deal with the economic challenges related to low stabilization pathways.

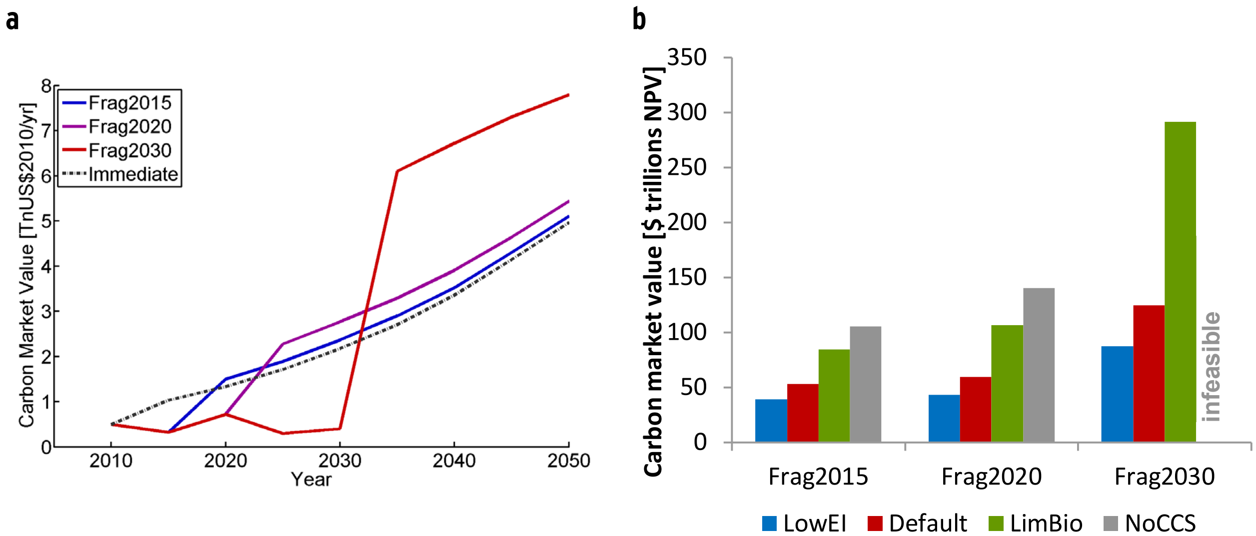
Managing the economic challenges and distributional questions associated with stringent climate change mitigation requires strong international and domestic institutions. Even if a comprehensive global agreement is implemented soon enough to avoid high aggregate economic costs, the impacts of policies will be felt harder during the initial transition period and, depending on the policy design, will likely raise distributional issues among and within countries. To avoid that the costs of mitigation policies fall disproportionately on the poor and to help consumers and businesses deal with policy-induced energy price increases requires effective institutions. Similarly, strong institutions are needed to help manage potential challenges arising from energy system transformations such as the impact of bioenergy on land use and nuclear power safety standards.

Figure 6: (a) Development over time of final energy prices indexed to 2010 under climate policy regimes *Frag2015*, *Frag2020* and *Frag2030* as well as baseline conditions. (b) shows the short term energy price increase (first decade after target implementation) induced by climate polices, measured as difference to baseline (BAU) for different start dates of climate policies, and selected technology scenarios.



Energy price increases are among the most direct impacts of climate policies on households and firms. Their impact depends on the rate of the increases: if energy prices rise quickly, there is little time for adaptation through technological or behavioral changes. We assume that even without climate policy, energy prices would increase at a rate of roughly 20% per decade. If a comprehensive global agreement is reached by 2015 and the default portfolio of mitigation options is available, pursuing the 2°C target leads to an additional energy price increase of around 20 percentage points over the first decade of implementation. Delaying a cooperative agreement until 2030 results in much stronger short-term price increases of up to 100 percentage points (Figure 6). Various industrialized countries have recently adjusted to strong energy price increases. For example, household electricity prices in Germany rose by 60% between 2000 and 2010 and US gasoline prices more than doubled between 1998 and 2008 (ENERDATA 2013). For developing countries, however, there is some evidence that rapid increases in energy prices can be causes of social unrest (Morgan 2008).

Figure 7: (a) Development over time of carbon market value under the climate policy regimes *Frag2015*, *Frag2020* and *Frag2030* as well as immediate climate policy. (b) shows the aggregated carbon market value, cumulated over 2010-2100 and discounted at 5%..



Climate policies that are both stringent and efficient require carbon prices that are harmonized across regions and sectors so as to ensure equal mitigation costs at the margin (Stern 2007). Harmonizing carbon prices presents an institutional challenge as it raises the question of how to account for the needs of more vulnerable regions and sectors and how to distribute the potentially large revenues. This is true regardless of whether the approach is to harmonize carbon taxes among countries with very different economic conditions or to create an international emissions trading scheme that involves the allocation of national emission budgets and international capital flows. We can assess the potential distributional challenge of such capital flows by looking at the market value of the emissions covered by carbon pricing. Assuming a global cap and trade system starting in 2020 and achieving emissions reductions in line with the 2°C target, we find that the cumulated present value of emissions permits over the 21^{st} century amounts to about US$50 trillion under default technology assumptions (Figure 7). This is comparable to the market value of crude oil consumed over the same period in the absence of climate policy. The distributional challenges are even larger if a global agreement is not reached before 2030 or if critical technology options are limited. For instance, if bioenergy availability is limited in order to reduce land use conflicts, the carbon market value more than doubles.

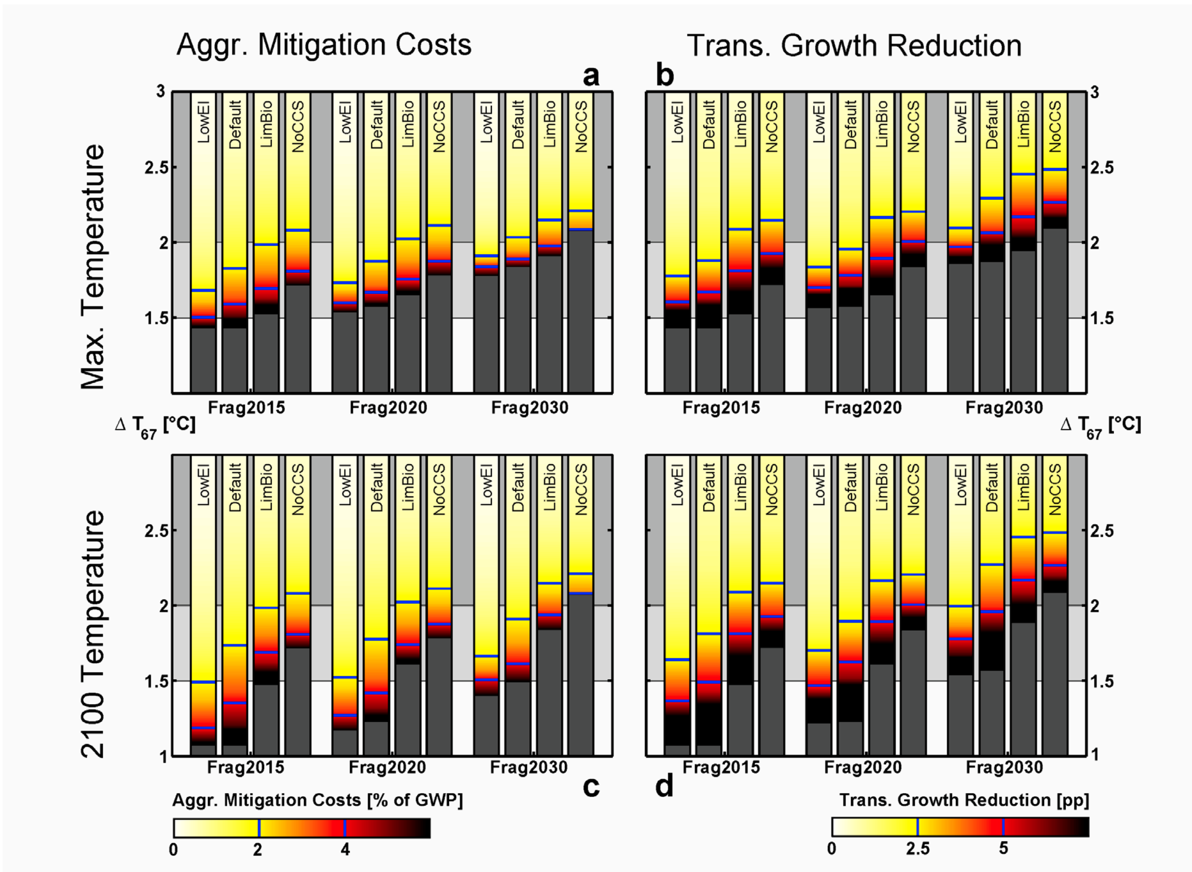
Higher carbon market values imply higher stakes in the haggling about the distribution of policy costs and benefits across countries, economic sectors and societal groups. In any case, strong institutions are needed both at the national and international level to ensure that climate policies are implemented in a fashion that is widely accepted as fair and equitable.

(6) A further delay of climate policy increases the lower limit of achievable climate targets

Unless societies develop an unprecedented willingness to voluntarily accept short-term economic pain for long-term environmental gain, climate policies can only be successfully implemented if economic impacts can be kept at a moderate level. We estimate that the lower limit of achievable climate targets is roughly 1.7°C if comprehensive mitigation policies are agreed upon in 2015 and implemented by 2020 and the full portfolio of technologies is available. This estimate assumes the maximum acceptable economic impacts to be aggregate mitigation costs of 4% of GWP, a short-term reduction of net income growth of 5 percentage points, an aggregated carbon trade volume of US$ 100 per ton, and a short-term energy price increase induced by climate policy of 100 percentage points.

If comprehensive global climate policies are delayed by another 15 years, the lower limit of achievable climate targets increases by about 0.4°C because of the effects of delay on income growth during the transition phase (Figure 8). Similarly, unavailability of CCS increases the lower limit by about 0.3°C. The door to climate stabilization remains ajar, but with every year of policy delay it closes further, increasing the reliance on critical technologies.

Figure 8: (a) Overview of the combined effects of mitigation timing and technology availability on achievability of either not-to-exceed targets (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 maximum 2010-2100 temperature increase (a,b) or 2100 temperature increase (c,d). Dark grey areas at the base of bars indicate temperature target levels that were not achieved with the range of carbon price paths assumed.



(7) It is unlikely that we can prevent temperatures from exceeding 1.5°C over the course of the 21st century. Returning to 1.5°C by 2100 would require a massive policy effort and the large-scale generation of negative emissions.

For the preceding analysis, we focused on climate outcomes in terms of maximum temperature increases in the 2010-2100 period. This is equivalent to formulating climate targets as “not-to-exceed” targets. Our modeling shows that it is unlikely that global warming can be kept below 1.5°C throughout the century. However, if temperature levels in 2100 are considered instead of maximum temperatures over the time frame of 2010–2100, lower climate targets are achievable despite a temporary overshooting of the target. In this interpretation, the 1.5°C target is very ambitious, but not out of reach. Temperature levels in

2100 can only be limited to 1.5°C without major economic disruptions if comprehensive global emissions reductions commence by 2020 and if biomass in combination with carbon capture and storage (BECCS) is deployed at a large scale. This underscores crucial tradeoffs between climate target stringency and adverse environmental and societal side-effects, such as those implied by large-scale bioenergy use.

Overall, we find that technology portfolios have an even more critical influence on achievable 2100 temperature levels than on maximum temperatures. 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.

4 Conclusion

The combined analysis of policy frameworks and technology availability suggests that reaching the 2°C target with a 67% likelihood essentially requires the adoption of global cooperative action in the coming ten years and the deployment of CCS technologies. If CCS technologies are not part of the available technology portfolio, it becomes increasingly difficult to achieve the 2°C target. All indicators suggest that a delay in comprehensive emissions reductions or limited availability of crucial mitigation technologies would significantly increase the costs and transitional challenges of mitigation and would render the achievability of the 2°C target questionable.

Distributional questions and concerns about the economic costs of mitigation are important factors behind the difficulty of finding a global agreement on climate change mitigation. However, the longer the international community delays the implementation of comprehensive climate policies, the more weight these issues will gain and the more challenging it will be to resolve them. In addition, delays in global mitigation efforts will increase the relevance of the option of net-negative emissions through bioenergy carbon capture and storage – a technology solution with potentially large negative side effects such as competition with arable land for food crops. The challenges resulting from policy delay could reduce the international community's determination to meet stringent climate targets, which in turn would increase the risk of irreversible climate disruptions and severe harm to regions that are vulnerable to climate change. . On the other hand, our results show that the adoption of a global agreement in the coming years that would initiate cooperative action within the coming ten years would allow the international community to reach the 2°C target with high likelihood. However, keeping the economic costs of mitigation within moderate bounds would require a broad portfolio of technology options for low-carbon energy supply and energy efficiency as well as efficient policies and strong institutions.

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