Supplementary Information:

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

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1 Methods

Our analysis combines a state-of-the-art integrated energy-economy-climate model (REMIND) with the probabilistic reduced-form climate model MAGICC. The following sections provide an overview of these modeling frameworks.

1.1 The integrated energy-economy-climate model REMIND

We use version 1.5 of the energy-economy-climate model REMIND to derive greenhouse gas (GHG) emission pathways and policy cost estimates for a large ensemble of mitigation scenarios with different assumptions on technology availability, timing of cooperative action, and carbon price levels under a global cooperative climate policy regime.

A detailed description of REMIND 1.5 is available from (Luderer *et al* 2013b). REMIND is a global model of the energy-economy-climate system spanning the period 2005-2100, with 5-year time steps between 2005 and 2060, and ten year time steps thereafter. The macro-economic core of REMIND is a Ramsey-type intertemporal general equilibrium model in which global welfare is maximized, as found in similar form in other integrated assessment models such as RICE (Nordhaus and Yang 1996) or MERGE (Manne *et al* 1995). The model computes a unique Pareto-optimal solution which corresponds to the market equilibrium in the absence of non-internalized externalities. The world is divided into 11 regions: there are five individual countries (China, India, Japan, United States of America, and Russia) and six aggregated regions formed by the remaining countries (European Union, Latin America, Sub-Saharan Africa without South Africa, a combined Middle East / North Africa / Central Asia region, Other Asia, Rest of the World). Trade is explicitly represented for final goods, primary energy carriers, and, in case of climate policy, emission allowances. Macro-economic production factors are capital, labor, and final energy. The economic output is available for investments into the macro-economic capital stock as well as for consumption, trade of goods, and financing the energy system.

The macro-economic core and the energy system module are hard-linked via final energy demand and costs incurred by the energy system. Economic activity results in demand for final energy such as transport energy, electricity, and non-electric energy for stationary end-uses. This final energy demand is determined by a production function with constant elasticity of substitution (nested CES production function). The energy system module accounts for endowments of exhaustible primary energy resources (coal, oil, gas and uranium) as well as renewable energy potentials (biomass, hydro power, wind power, solar energy, geothermal energy). REMIND represents capacity stocks of more than 50 technologies for the conversion of primary energy into secondary energy carriers as well as for the distribution of secondary energy carriers to end use sectors. In particular, the model accounts for the possibility of combining fossil fuel and bioenergy use with carbon capture and storage (CCS). Since trees and crops extract CO_2 from the atmosphere, deploying bioenergy in combination with CCS (BECCS) can result in net negative emissions. As shown by the results for technology-constrained scenarios, BECCS technologies are of crucial importance for the achievability of low stabilization targets. Learning-by-doing effects are explicitly represented via learning curves for wind and solar technologies as well as electric vehicles. REMIND does not have any hard limits on the expansion rate of new technologies. In order to mimic real-world inertias in technology up-scaling, a cost penalty ("adjustment costs") is applied that scales with the square of the relative change in capacity investments. This yields technology diffusion rates that are broadly in line with historical patterns (Wilson *et al* 2013). The retirement of fossil capacities before the end of their technological life-times is possible, but limited to a rate of 4% per year.

REMIND calculates energy related non-CO_2 GHG and aerosol emissions via time-dependent emission factors. Emissions from agriculture and land-use are obtained from the land-use model MAgPIE (Lotze-Campen *et al* 2008). Emission reduction potentials of non-energy related CO_2, CH_4 and N_2O emissions are represented via marginal abatement cost curves. Emissions of F-Gases are prescribed exogenously based on RCP data (van Vuuren *et al* 2011a).

REMIND has been used for numerous analyses of the economics of climate change mitigation (Leimbach *et al* 2010a, 2010b, Bauer *et al* 2012a, Lueken *et al* 2011, Bauer *et al* 2012b, Luderer *et al* 2012c). REMIND has also participated in a number of past model inter-comparison exercises (Edenhofer *et al* 2010, Luderer *et al* 2012a, Calvin *et al* 2012), and is currently involved in several on-going inter-comparison exercises.

1.2 The probabilistic climate model MAGICC

To represent uncertainties in the carbon cycle and climate system response to emissions, we employ the reduced complexity climate model MAGICC (version 6) (Wigley and Raper 2001, Meinshausen *et al* 2011c, 2011a). Here, we employ a probabilistic setup of the model. The parameter space has been constrained by historical observations of ocean heat uptake (Domingues *et al* 2008) and surface temperatures over land and ocean in both hemispheres (Brohan *et al* 2006), using a Metropolis Hastings Markov Chain Monte Carlo approach as described in (Meinshausen *et al* 2009). A 600-member ensemble of the resulting joint distribution of the 82-dimensional parameters space has then been drawn, so that the marginal climate sensitivity distribution closely represents the IPCC Fourth Assessment Report conclusions in regard to our uncertainty on climate sensitivity (Rogelj *et al* 2012) . Differently to the setup in (Meinshausen *et al* 2009, Rogelj *et al* 2012), we include a probabilistic permafrost module (Schneider von Deimling *et al* 2012)—thereby accounting for the effect of potential climate feedback from permafrost by additional release of carbon dioxide and methane release from the upper soil compartment. The omission of the permafrost feedback effect has previously been regarded as a research gap (Hatfield-Dodds 2013), although we note that the temperature effect until 2100 is limited.

We consider all important greenhouse gases, tropospheric ozone precursors, the direct and indirect aerosol effects and landuse albedo. CO_2, CH_4, N_2O, sulfur, black carbon and organic carbon emissions are endogenous results from the REMIND model, while other forcing components are complemented from corresponding RCP emission scenarios (van Vuuren *et al* 2011a, 2011b, Masui *et al* 2011). For emissions of ozone depleting substances we assume the WMO2006 emissions scenario – consistent with the setup for creating the RCP GHG concentration profiles (Meinshausen *et al* 2011b).

2 Scenario design

Our analysis is based on a large set of climate mitigation scenarios compiled along the dimensions of (i) timing of global cooperative mitigation action, (ii) availability of low carbon technologies, and (iii) stringency of long-term climate policies, controlled by different globally harmonized carbon price levels. The combination of these dimensions yields a scenario ensemble of 285 different REMIND runs, each representing one energy-economic development pathway. For each scenario, the GHG emission trajectories resulting from REMIND were used to calculate 600 climate realizations with the probabilistic climate model *MAGICC*, yielding a total of 171’000 climate model simulations. The variations along the different scenario dimensions are presented and motivated in the following.

2.1 Timing of climate policy

In the long-term, any climate stabilization target requires near-zero emission levels. As a consequence, climate policy will only be successful if it eventually establishes a comprehensive climate regime that covers virtually all countries and emitting sectors. The second scenario dimension explores delay in setting up such a global comprehensive climate policy regime. The specifications of the delayed-action scenarios follow those of the RoSE study (Luderer *et al* 2013a).

P0. Weak-policy baseline (WeakPol)

This scenario is designed as a reference scenario that includes weak climate policies. It is meant to represent the unambitious end of short- and long-term climate policy developments. It was constructed by considering existing climate policies, a weak interpretation of the 2020 Copenhagen Pledges, and an extrapolation of these targets beyond 2020 based on emissions intensity (GHG emissions per unit of GDP). Three country groups are considered: industrialized countries (Group I), developing countries excluding resource exporters (Group II), and fossil resource exporters of the former Soviet Union and Middle East (Group III). Climate policy is assumed to remain fragmented, with no emissions trading between regions until 2020. Limited trading of emissions between industrialized and developing countries is allowed after 2020. It is assumed that resource-exporting countries (Group III) will not adopt any binding targets. Furthermore, it is assumed that land-use emissions will not be subject to carbon pricing. A detailed description of the *WeakPol* scenario is provided in Section SI 6. The assumptions of the *WeakPol* scenarios with regard to regional emission reduction targets are identical to those used in Luderer et al. (2013).

P1. Weak and Fragmented climate policy until 2015 (Frag2015)

The *Frag2015* scenario considers the most optimistic possible outcome of the current climate negotiation process and the Durban Platform. It assumes that a global climate agreement is reached by 2015, and that comprehensive emission reductions are implemented from 2020 onwards. Until 2015, the model follows the weak policy scenario, without anticipating more stringent future climate policies. Starting with the 2020 model time step, a global cooperative climate regime is implemented with comprehensive regional and sectoral coverage.

P2. Weak and Fragmented climate policy until 2020 (Frag2020)

The *Frag2020* scenario considers a somewhat more pessimistic outcome of the Durban Platform, assuming that it fails to deliver 2020 emission reductions beyond those of the current pledges as implemented in the *WeakPol* scenario, and that the implementation of comprehensive global emissions reductions is delayed until 2025.

P3. Weak and Fragmented climate policy until 2030 (Frag2030)

The *Frag2030* scenario assumes a failure of the Durban Platform negotiations, resulting in unambitious and fragmented climate policies following the *WeakPol* scenario without anticipating more stringent future climate policies until 2030. Comprehensive global emissions reductions start in 2035.

P4. Immediate action (Immediate)

In the immediate action scenario we assume that global cooperative climate mitigation policies start immediately, with global comprehensive emission reductions starting in the 2015 model time step. It must be considered hypothetical, since none of the current climate negotiation tracks would be able to deliver such an outcome.

2.2 Technology availability

Earlier studies (Azar *et al* 2010, Edenhofer *et al* 2010, Tavoni *et al* 2012) have shown the crucial importance of low-carbon technologies for costs and achievability of low stabilization targets. To further explore the influence of technology availability on the lower limit of achievable climate targets, we produced seven scenario sets with different idealized assumptions on technology availability. With the exception of the the *NoBECCS* case, the scenario specifications are identical to those used in the EMF27 study (Kriegler *et al* 2013):

T1. Full technology portfolio (Default)

All technologies represented in the REMIND model are assumed to be available. Default assumptions regarding final energy demand are implemented, with autonomous energy intensity improvements (AEII, i.e., reductions in final energy demand per unit of GDP in absence of climate policy) in line with the historical rate of about 1.2%/yr. Bioenergy use is limited to 300 EJ/yr.

T2. No carbon capture and storage (NoCCS)

All conversion technologies with carbon capture and storage, both with fossil fuels or bioenergy as feed-stocks, are excluded from the mitigation portfolio. This scenario setting is motivated by the slow progress in up-scaling CCS to commercial scale, potential environmental impacts and limited public acceptance of geological storage in some countries, as well as institutional barriers.

T3. No bioenergy combined with carbon capture and storage (NoBECCS)

All technologies that combine bioenergy use with carbon capture and storage are excluded from the mitigation portfolio. Specific challenges applying to BECCS in addition to those of CCS include (a) the lower technological maturity of BECCS technologies, (b) sustainability constraints to bioenergy production (see LowBio case), (c) institutional challenges related to incentivizing negative emissions.

T4. Low bioenergy availability (LimBio)

The global bioenergy potential is limited to 100 EJ. This scenario is motivated by a variety of concerns about the sustainability of large-scale bioenergy production regarding (a) scarcity of arable land, (b) potential freshwater demand for irrigation, (c) effect on food prices, (d) potential indirect land-use change emissions (ILUC) induced by bioenergy production, and (e) potential loss of biodiversity.

T5. Nuclear phase-out (NucPO)

No nuclear capacity additions beyond those currently under construction. This scenario is motivated by limited public acceptance of nuclear power in view of (a) security concerns in the aftermath of the Fukushima accident, (b) challenges related to nuclear waste disposal, and (c) proliferation concerns.

T6. Limited Wind and Solar Power (LimSW)

The share of electricity production from wind and solar power is limited to 20% of total electricity in each region. This scenario is motivated by the challenges related to the fluctuating supply from variable renewable energy sources.

T7. Low energy intensity (LowEI)

This set of scenarios assumes autonomous energy intensity improvements that are higher than those in the *Default* scenario, and exceed those observed historically. Baseline energy intensity is 25% lower than in *Default* in 2050, and 40% lower than in *Default* in 2100. The *LowEI* scenarios describe a world in which behavioral changes result in lower demand for final energy, and barriers for energy efficiency improvements are decreased.

2.3 Carbon price levels

We explore the effect of long-term climate policy stringency on climate stabilization levels and mitigation costs by varying the uniform carbon price signal applied in the global cooperative climate regime. We use 2020 reference carbon price levels of 5, 10, 20, 30, 40, 50, 100, 200 and 500 US\$2005/tCO_2. Since the model's responsiveness to carbon pricing is highest at low to medium prices, we chose to use more narrowly spaced price steps below 50 US\$2005/t CO_2. By default, we assume carbon prices to increase by 5% per year. This rate is very close to the model-endogenous discount rate, thus implying inter-temporal efficiency in minimizing cumulated GHG emissions. Section SI 4 explores the sensitivity of the results to the development of carbon prices over time.

We derived emission prices for non-CO_2 Kyoto gases based on global warming potentials from the IPCC AR4. We also calculate *Baseline* scenarios without any climate policies as a baseline for measuring the effect of mitigation.

3 Economic indicators of the mitigation challenge

For the analysis, we derived four indicators as proxies for the potential economic and political challenges associated with the implementation of climate policies: (i) aggregated mitigation costs as a measure for costs in the long run, (ii) transitional consumption growth reduction as a proxy of short-term economic effects, (iii) the aggregated carbon trade volume as a proxy for potential distributional conflicts under an international cap-and-trade system, and (iv) transitory energy price increases during the phase-in of comprehensive climate policies. They are defined and motivated in the following.

3.1 Aggregated mitigation costs (AMC)

Aggregate mitigation costs quantify the inter-intertemporally aggregated impact of climate mitigation policies on affluence. They are commonly used for characterizing long-term mitigation scenarios (B.S. Fisher *et al* 2007, Edenhofer *et al* 2010, Luderer *et al* 2012a). We calculate them as aggregated discounted consumption losses expressed relative to aggregated, discounted gross world product *GWP* in the baseline:

$$AMC = \left(\sum_{t=2010}^{2100} (C_{Baseline} - C_{Pol}) \cdot (1+\delta)^{2010-t}\right) \Big/ \left(\sum_{t=2010}^{2100} GWP_{Baseline} \cdot (1+\delta)^{2010-t}\right) \cdot 100\%,$$

where C denotes consumption, and a discount rate $\boldsymbol{\delta}$ of 5% p.a. is used. While aggregated mitigation costs typically only amount to a few percent of cumulative economic output, they can be very significant in absolute terms. For the REMIND GWP baseline used here, each % of cumulative costs corresponds to discounted aggregated costs of US\$ 19.6 tn in values of 2010. We use reference mitigation cost values of 2% and 4% of GWP for the analysis of climate target achievability. This can be compared to the target to devote 0.7% of the gross national product (GNP) of OECD countries to Official Development Assistance (ODA) (United Nations 2002).

3.2 Transitional growth reduction (TGR)

Economic losses occurring during the transition from a regime without climate policy to a regime with stringent climate policies are a crucial barrier to the implementation of climate policies. We define the transitional growth reduction as the maximum of the difference between decadal consumption growth rate in the baseline and in the policy scenario, in units of percentage points [pp]:

$$TGR = \max_{2010<t<2050} \left(g_{Baseline}(t) - g_{Pol}(t)\right),$$

where for each scenario

$$g(t) = \left(C(t+5\text{a}) - C(t-5\text{a})\right) / \, C(t) \cdot 100\ \%$$

is the decadal rate of consumption growth in units of %.

In the baseline, i.e., without climate policies, globally aggregated consumption grows at a rate of around 30-40 % per decade in the first half of the 21st century. The transition from a weak, fragmented climate policy regime to a regime with stringent and comprehensive emission reductions can slow consumption growth markedly. The timing of climate policy has important implications for the incidence of mitigation costs over time (see Figure 3 in the main paper). In case of immediate action, costs for reaching the 2°C target with a high likelihood are well below 1% of gross world product (GWP) in 2020 and increase gradually over time. For the scenarios with delayed cooperative action, the picture looks different: As the weak policies only have a small effect on the economy, near-term costs in the delayed scenarios with delayed cooperative action are rather small. Once a stringent global climate regime is implemented, however, costs increase to levels that exceed those in the immediate scenario reaching the same long-term target.

In some extreme scenarios, the transition from the weak, fragmented climate policy regime to stringent climate policies can therefore result in transitory mitigation costs of 10pp or higher. Such dramatic short-term effects render the political feasibility of such pathways questionable. For comparison, based on the IMF data (IMF 2012) the financial crisis of 2008 can be estimated to have reduced global economic output by around 5%.

Another study estimated the effect on the economies of the US and Europe to be of similar magnitude (Gros and Alcidi 2010). For the purpose of this study, we use a reference range of 2.5-5 pp to examine how climate policy induced consumption growth reductions limit economically achievable climate targets.

3.3 Energy price increases (EPX)

Energy price increases are among the most direct impacts of climate policies on households and firms. The impact of high energy prices will depend on the rates of price increases: if energy prices rise quickly, there is little time for adaptation through technological or behavioral changes.

To examine the effect of climate policies on energy prices, we derive a global final energy price index recursively, by calculating the market value of the final energy demand basket at time *t* relative to the price the same final energy basket would have cost one period, i.e., 5 years, earlier:

$$EPX(t) = EPX(t-5a) \cdot \sum_r \sum_i p_{i,r}(t)\, FE_{i,r}(t) \Big/ \sum_r \sum_i p_{i,r}(t-5a)\, FE_{i,r}(t)$$

where $p_{i,r}$, $FE_{i,r}$ are the demands and prices of final energy carrier *i* in region *r*, respectively, and *EPX(*2010*)* is set to unity for normalization. This method is akin to the calculation of a chained consumer price index. The decadal growth rate of the energy price index can be readily calculated as

$$g_{EPX}(t) = (EPX(t+5\text{ a}) - EPX(t-5\text{ a}))/\, EPX(t) \cdot 100\ \%$$

The maximum climate-policy-induced short-term energy price increase, in units of percentage points [pp] follows as

$$EPI = \max_{2010<t<2050} \left(g_{EPX,BaU}(t) - g_{EPX,Pol}(t)\right).$$

Figure S1a shows the development of the global energy price index over time. Energy prices would increase by a rate of roughly 20% per decade even if no climate policies were implemented, reflecting increasing global energy demand and a gradual depletion of fossil resources. Climate policy adds to this. In the *Frag2015* scenario and under *Default* technology assumptions, reaching the 2°C target implies a maximum additional energy price increase of around 20 pp in the decade following the implementation of the mitigation target. A further delay of a cooperative agreement results in much stronger short-term price increases of up to 100 pp in *Frag2030* (Figure 2d in the main paper).

Recently, substantial price increases have occurred in various industrialized countries, such as a 60% price increase in household electricity prices in Germany between 2000 and 2010, or a more than 100% price increase for gasoline in the US between 1998 and 2008 (ENERDATA 2013). For developing countries, there is some evidence that increases in energy prices can be causes of social unrest (Morgan 2008). For instance, a 70% increase of gasoline prices and a trebling of electricity prices (albeit in a much shorter time frame than a decade) were an important trigger for riots that occurred in Indonesia in 2008 (Purdey 2006). This leads us to assume that critical levels of transitional, climate-policy-induced energy price increases might be in the range of 50-100 pp.

3.4 Carbon market value (CMV)

Not only aggregated costs, but also distributional effects of climate policy matter. In order for climate policies to be efficient, carbon prices need to be harmonized across regions and sectors, so as to ensure equal mitigation costs at the margin (Stern 2007). While carbon pricing results in costs for emitters, it also produces potentially large revenues, for instance for the government in case of a carbon tax or full auctioning of emission permits in the context of an emissions trading scheme. Similarly, in the context of an international emissions trading scheme, the allocation of the permissible emissions budget across individual countries determines capital flows induced by emissions trading, and therefore has strong distributional implications (Lueken *et al* 2011, Luderer *et al* 2012b). We therefore use the cumulated carbon market value as an indicator of the institutional challenges to manage distributional conflicts arising from emissions trading both on the national and international level, and define it as

$$CMV = \sum_{t=2010}^{2100} p_{CO2}(t) \cdot E(t) \cdot (1+\delta)^{2010-t}$$

where E refers to all positive greenhouse gas emissions, but excludes negative emissions from BECCS, and $p_{CO2}(t)$ is the price of CO_2.

The carbon market value as a function of temperature levels is quite sensitive to timing of mitigation action and technology availability. In the *Frag2015* scenario, reaching the 2°C target with a cap-and-trade regime that covers all regions and sectors implies an aggregated carbon market value of about US$ 56 tn in values of 2010 (Figure 2c). The aggregated market value of fossil fuels consumed in a baseline scenario without climate policy is similar in magnitude, with oil accounting for US$ 46 tn, and coal, oil and gas combined for US$ 83 tn in values of 2010. We therefore assume that critical levels for the inter-temporally aggregated carbon market value might be in the range of US$2010 50-100 tn.

4 Sensitivity of aggregated mitigation costs to the discount rate

Since mitigation costs as a share of GWP are not constant over time (Figure 3b of the main paper), aggregated mitigation depend indeed on the discount rate used for the inter-temporal aggregation. To ensure consistency with the investment dynamics of the model, a discount rate of 5% p.a. was used for the calculation of the aggregated mitigation costs, which is in good agreement with the interest rate that emerges endogenously in the model (and historically observed rates of return on equity, see (Gollier 2012)). From the perspective of a representative household, the discount rate depends on two other ethical parameters, rate of pure time preference and the elasticity of marginal utility (Ramsey 1928). Alternative choices of these parameters can result in either lower or higher social discount rates. In the aftermath of the Stern Review (Stern 2007), a fierce debate about the appropriate use of discount rates in the economics of climate change emerged (Nordhaus 2007, Mendelsohn *et al* 2008, Weitzman 2007, Dasgupta 2006, Dietz and Stern 2008). Figure S4 shows a sensitivity study of aggregated mitigation costs for discount rates of 2.5%, 5% and 7.5% p.a. We find that a lower discount rate results in a higher aggregated costs indicator (since it puts more weight to the long-term costs, which are higher as a share of GWP) and a stronger economic penalties of delayed action.

5 Sensitivity of the results to the implementation of climate policies

We implemented long-term mitigation policies in terms of exponentially increasing carbon price pathways (cf. Section SI 2). In principle, other approaches are conceivable for representing climate policies in the model. Here we show that the approach taken represents close-to-optimal climate policies, and therefore allows us to explore the efficient frontier in the trade-off between climate targets and economic costs. The optimal pricing over time of the limited remaining atmospheric carbon budget implied by a given climate target (Meinshausen *et al* 2009, Matthews *et al* 2009) is directly related to the economics of exhaustible resources, and is therefore akin to the optimal pricing of coal, oil and gas. Therefore, the Hotelling-rule (Hotelling 1931) can be applied. According to this rule, an inter-temporally optimal abatement strategy implies that carbon prices increases at the discount rate, in order to fulfill the intertemporal arbitrage condition determining the optimal use of the imposed carbon budget over time. The rate of increase of 5% p.a. that we assumed in our policy scenarios is close to the discount rate that emerges endogenously in REMIND, which is around 5-6 p.a. Therefore, a scenario experiment with an inter-temporal GHG emissions budget yields results that are very similar to those obtained from carbon price scenarios with comparable stringency (Figure S4).

There is no perfect correlation between the GHG emission budget and maximal 21st century temperature increases, especially in the case of delayed action scenarios with overshooting temperatures. We therefore explore the effect of implementing climate policy in terms of explicit not-to-exceed temperature targets. This allows the model to exploit flexibilities in adjusting the development of price ratios between long-lived and short-lived greenhouse gases over time and across different greenhouse gases (Manne and Richels 2001). We observe that the resulting aggregated mitigation costs implied by a certain maximum 21st century temperature are only marginally below the achievability frontier derived based on exponentially increasing carbon prices with global warming potentials (Figure S4a). On the other hand, the implementation in terms of explicit not-to-exceed temperature targets results in significantly higher costs as a function of 2100 temperature levels for temperature targets lower than 2°C. The reason for this is that a stringent GHG tax/budget scenario leads to temperature overshooting in the 21st century, while a not-to-exceed temperature target creates no incentive to reduce temperatures below the maximum temperature reached around 2040-2080, even if such a reduction might be achieved at comparatively low cost (Figure S3b).

Finally, we examined if a slower phase-in of the carbon tax during the transition from weak to comprehensive climate policies can alleviate the economic shocks observed in delayed-action scenarios with stringent long-term targets. To this end, we ran *Frag2030* scenarios with a more gradual ramp-up of CO_2 price levels from ~30% of the reference price value in 2035 to the full reference price value in 2060. For these scenarios we found that the increase of maximum temperature counteracts the benefit in terms of lower economic challenges, both in terms of aggregated mitigation costs, and in terms of transitional consumption growth reductions. As a consequence these scenarios are in line with or above the achievability frontier constructed from the default price paths with exponentially increasing price levels.

6 Weak policy scenario

This section provides a detailed description of the weak policy scenario that we introduced as a reference point for the scenarios with a delay in global cooperative mitigation action. It is meant to represent the unambitious end of realistic short and long-term climate policy developments. It was constructed by considering existing climate policies, a weak interpretation of the 2020 Copenhagen Pledges applied to emissions from fossil fuels and industry, and an extrapolation of these targets beyond 2020 based on emissions intensity (GHG emissions per unit of GDP).

We consider three country groups: A group of industrialized countries (Group I, roughly corresponding to the OECD), developing countries without resource exporters (Group II), and fossil resource exporters (Former Soviet Union and Middle East, Group III). Climate policy is assumed to remain fragmented, with no emissions trading between regions until 2020. Limited emissions trading between industrialized and developing countries is allowed after 2020. Under *Default* technology assumptions, the *WeakPol* scenario results in 2020 greenhouse gas emission levels of 57.5 Gt CO_2e, consistent with the emissions estimate obtained in the latest UNEP gap report for the unconditional pledges under lenient rules(UNEP 2012). The specific assumptions for the eleven REMIND regions are described in the following.

Emission targets for industrialized countries (Group I)

For Group I countries, 2020 emission reduction targets are formulated relative to a base year (either 1990 or 2005). Unconditional emission reduction pledges were used where available. If a range for reduction targets is given, we used the lower end (weak interpretation) of pledges. Current long-term (2050) reduction ambitions are assumed to be watered down.

EU-27: 2020 ambition on the low end of its Copenhagen Pledges: 20% below 1990. This corresponds to a 13% reduction relative to 2005. Further, we assume that the 2050 emission reduction target is watered down to 40%, and 2100 reductions reach 80%, relative to 1990, respectively.

USA: The target to reduce emissions 17% below 2005 in 2020 is assumed not to materialize. Instead, we assume no emission reductions beyond those achieved in the baseline levels. Because of increasing use of natural gas results, baseline emissions in

2020 are 8% below 2005 levels. After 2020, the emissions cap is assumed to decrease by 0.5% per year in the period 2020-50, and 1% per year after 2050.

Japan: The 25% emission reduction pledge relative to 1990 is conditional, and therefore assumed not to materialize. Instead, we assumed a 10% emission reduction relative to 1990 by 2020, and a 40% reduction until 2050.

Rest of the World: The "Rest -of the World" region, largely composed of other states of the "Umbrella Group" (Canada, Australia, New Zealand), plus South Africa, are assumed to achieve combined 2020 emission reductions of 5% relative to 2005. Further, emissions are assumed to decrease by 0.5% per year in the period 2020-50, and 1% per year after 2050.

Emission targets for emerging economies and developing countries, excluding oil exporting countries

Developing countries have formulated their 2020 pledges in terms of (a) emissions reductions relative to baseline, or (b) reductions in carbon emission intensity of GDP relative to a base year. In absence of concrete pledges beyond 2020, we assumed yearly emission intensity improvements comparable to those implied by the 2020 pledges.

China: China pledged to "lower its carbon dioxide emissions per unit of GDP by 40-45% by 2020 compared to the 2005 level, increase the share of non-fossil fuels in primary energy consumption to around 15% by 2020 and increase forest coverage by 40 million hectares and forest stock volume by 1.3 billion cubic meters by 2020 from the 2005 levels." China is currently putting in place domestic measures to fulfill this pledge. We therefore assume that it fulfills the ambitious end of the pledge (-45%) for 2020. After 2020, China is assumed to continue to decrease the emissions per unit of GDP by 3% per year.

India: India pledged to "reduce the emission intensity of its GDP by 20 to 25% by 2020 in comparison to the 2005 level." In the REMIND scenarios, this target is not binding. We assume that India follows China in reducing emissions per unit of GDP by 3% per year after 2020.

Other Asia: Several other Asian countries have pledged substantial emission reductions relative to baseline—most notably, South Korea (30% relative to baseline) and Indonesia (26% relative to baseline). As a group, we assume other Asian countries to deliver emission reductions of -20% relative to baseline by 2020. After 2020, they are decrease the emissions per unit of GDP by 3% per year, equal to the decarbonization rate assumed for China.

Latin America: Several other Latin American countries have pledged substantial emission reductions relative to baseline—most notably the Brazil (36% below baseline) and Mexico (30% baseline), which account for a substantial share of Latin American emission. We assume that Latin America as a group will deliver 15% emission reduction from non-LUCF emissions. We further assume that LAM will reduce emission intensity by 2.5% per year in 2020-2050, and by 3% per year after 2050.

Sub-Saharan Africa (excl. South Africa) : Sub-Saharan Africa is assumed not to take any targets before 2020. After 2020-50, a reduction target of emission intensity per unit GDP of 2.5% per year is prescribed. However, this target is not binding, since economic growth exceeds emissions growth by more than 2.5% per year. After 2050, a target on the reduction of emission intensity per unit GDP of 3.5% per year is assumed.

Emission targets for resource exporters

The resource exporting REMIND regions (Middle East / North Africa / Central Asia and Russia) are assumed not to have an incentive to take any binding target. Countries of the Middle East have not pledged any emission reduction targets. Russia's unconditional target of -15 below 1990 is well above projected baseline emissions. Carbon leakage, i.e. higher emissions compared to baseline in Group III countries in response to climate policies in Group I and II countries is allowed.

Emission control in Sectors

We assume all Kyoto-Gas Emissions excluding land use, land use change and forestry (LULUCF) to be included in the reduction targets and subject to climate policies. Given higher institutional requirements for monitoring and reporting of land-use related CO_2 emissions, we assume climate policies to be ineffective in controlling LULUCF emissions. LULUCF emissions are thus assumed not to be subject to carbon pricing, and are not included in the emission reduction targets.

International Emissions Trading

In the Weak Policy Scenario, we assume global carbon markets to remain fragmented. Specifically, the following rules for the trade of emission allowances and intertemporal flexibility in the mitigation effort were assumed to apply:

- No emissions trading, nor banking or borrowing is permitted until 2020
- After 2020, unrestricted emissions trading between members of Group I

- After 2020, unrestricted emissions trading between members of Group II
- The total net import of Group I (from Group II) is restricted to 20% of the combined mitigation requirement of Group I (i.e., the difference between baseline emissions and emission allowances under the cap).
- Full when-flexibility is allowed within the periods 2020-2050 and 2050-2100.
- Excess emission allowances from 2020-2050 can be banked to the 2050-2100 period, but no borrowing from the second period is allowed in the first period.

Supplementary Figures

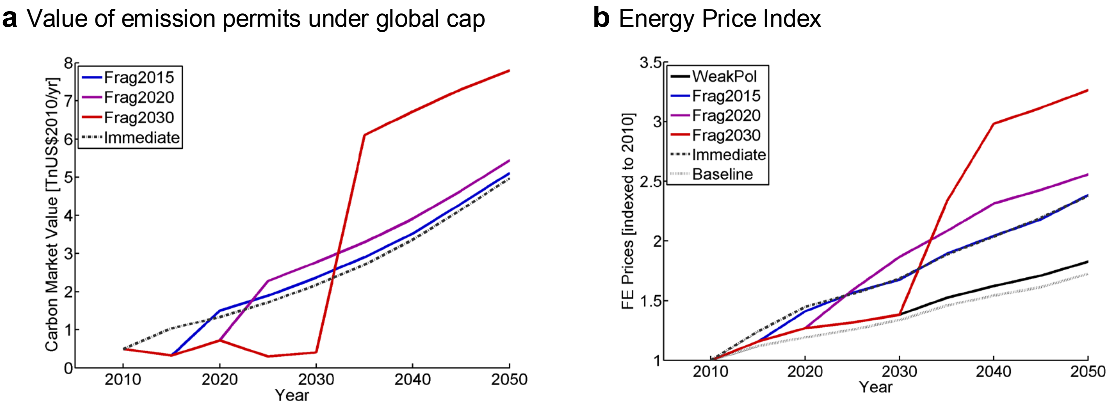

Figure S1: Effect of different near-term climate policy regimes on the development of (a) the value of emission permits under the global cap over time, and (b) the global energy price index. For the mitigation scenarios *Immediate, Frag2015, Act2030* and *Frag2030* cumulative emissions budget of 2500 $GtCO_2e$ were considered.

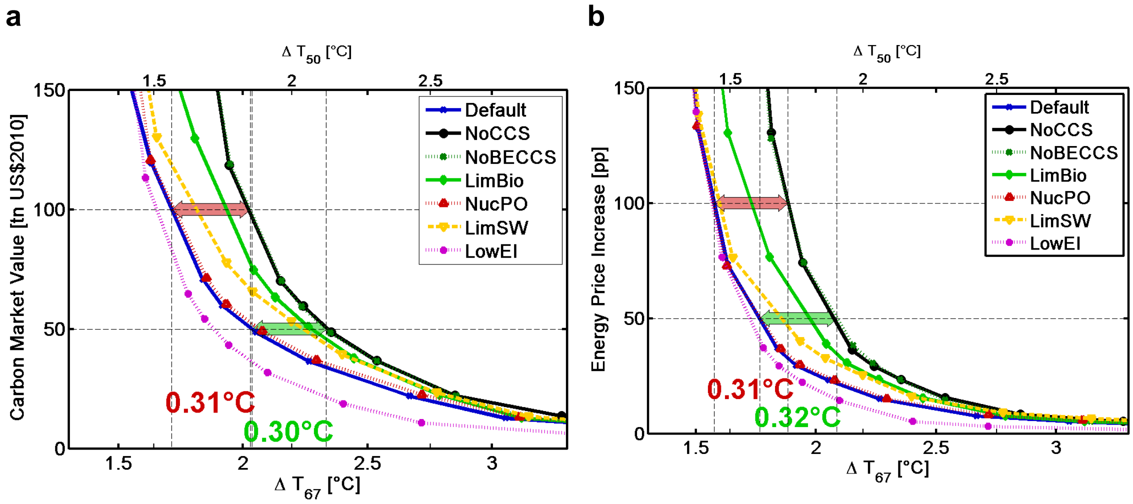

Figure S2: Temperature-cost-tradeoff curves showing the effect the technology availability on (a) carbon market value, and (b) energy price increase (*Frag2015* scenario). Temperature targets (maximum 2010-2100 temperatures) reached with a 67% likelihood (lower axis) or 50% likelihood (upper axis) are shown. Numbers indicate shift in terms of ΔT_{67}.

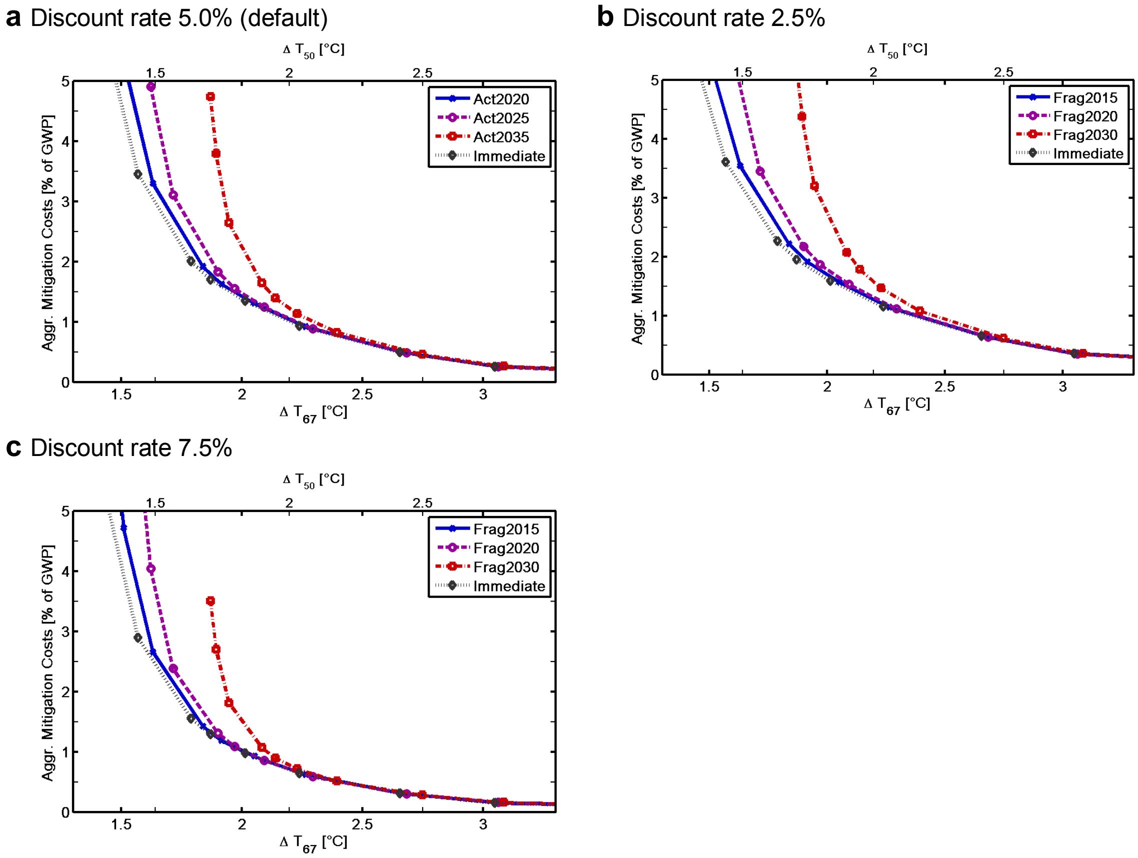

Figure S3: The sensitivity of aggregated mitigation costs to the choice of discount rate in the inter-temporal aggregation (cf. Fig. 2a of the main paper).

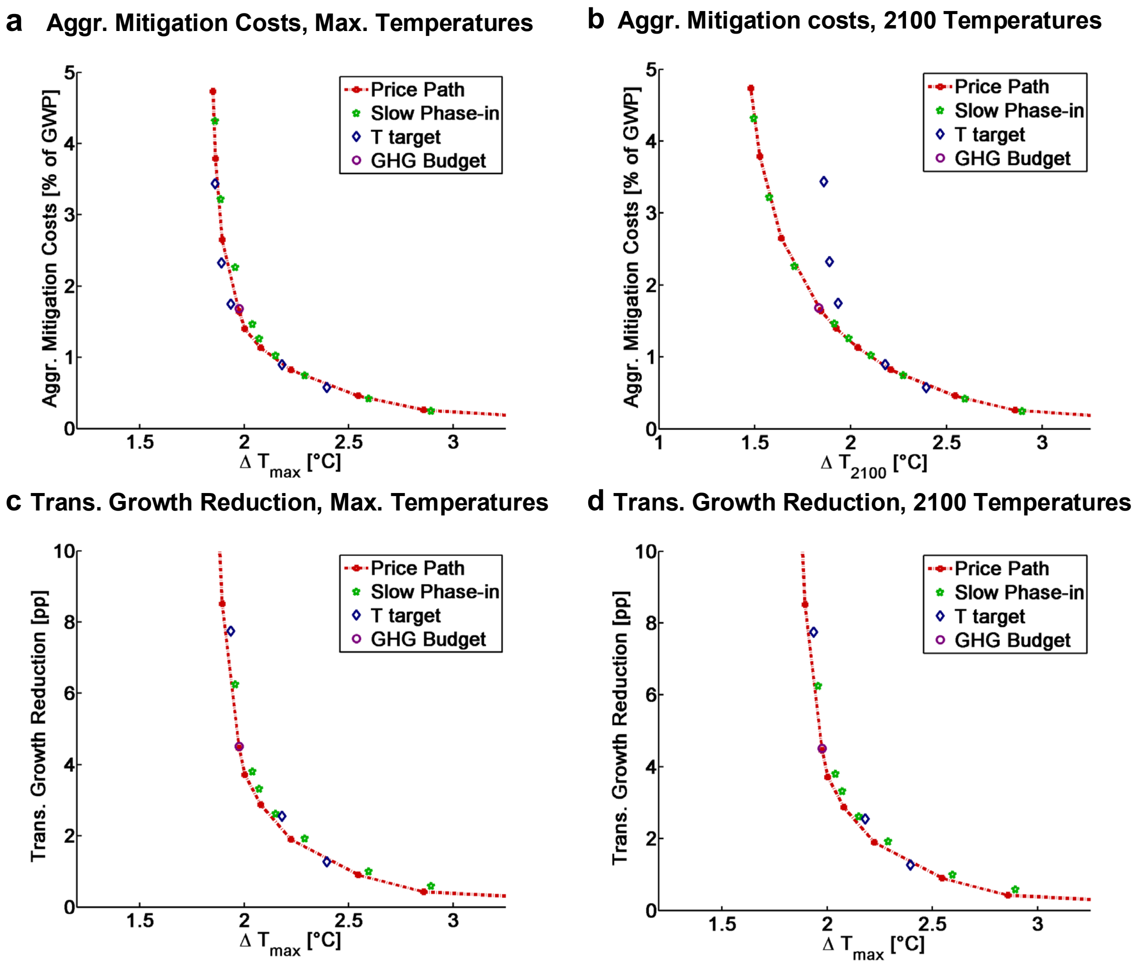

Figure S4: The effect of different climate target implementations examined for the example the *Frag2030* scenario with *Default* technology assumptions. In addition to exponential carbon price pathways (which are used for the analysis in the main paper), we show a scenario with a pre-scribed 2010-2100 GHG emission budget (purple circle), an explicit not-to-exceed temperature target (blue diamonds), and price paths with a slower phase-in of carbon prices. The results show that the temperature-cost trade-off curves derived based on exponential price paths are a robust indicator of the efficient achievability frontier for a given scenario setup.

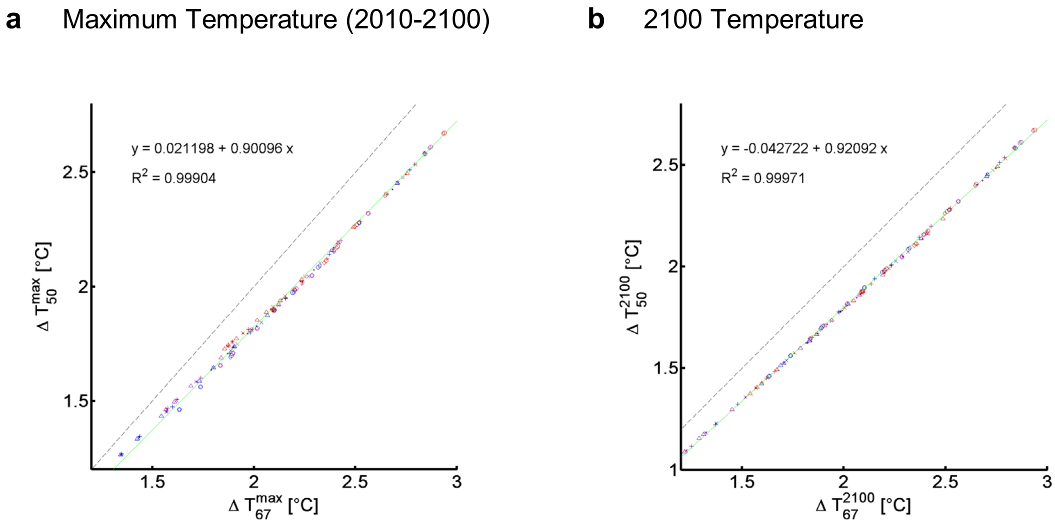

Figure S5: Correlation between temperature increases not exceeded with 67% and 50% likelihood for (a) maximum 2000-2100 temperatures, and (b) 2100 temperatures. Each individual data point corresponds to one climate mitigation scenario, with different colors indicating different assumptions along the delay dimension, and different markers correspond to different technology assumptions.

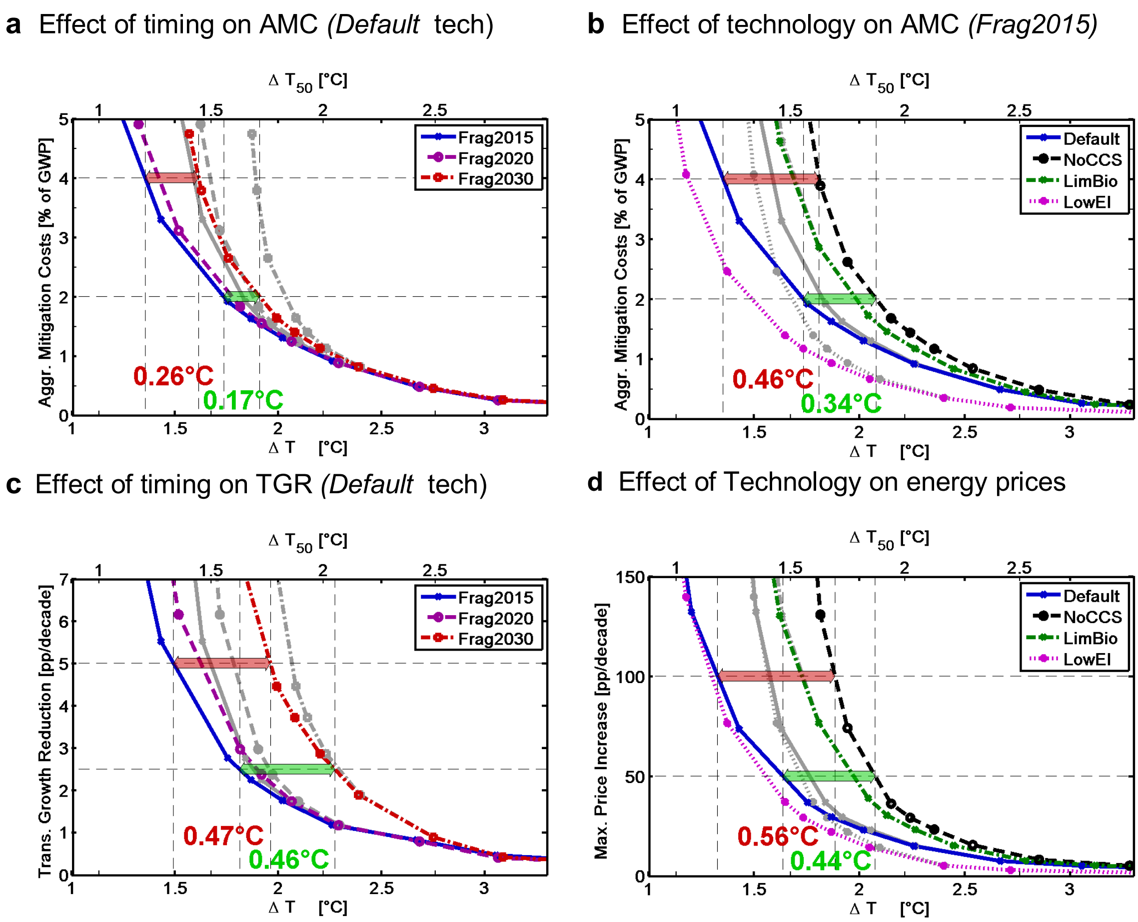

Figure S6: Temperature-cost tradeoff curves considering 2100 temperature levels. Grey lines indicate corresponding trade-off curves that consider maximal 2000-2100 temperatures. The left column shows the effect of mitigation timing, the right column the effect of technology availability. (a), (b) show aggregated mitigation costs, (c) shows transitional growth reductions, and (d) shows the maximum climate-policy induced decadal energy price increase. Note that for the *NoCCS* and *LimBio* scenarios, maximal temperatures are reached in 2100, therefore colored lines (2100 temperature) lie on top of the grey lines (maximal 21st century temperature).

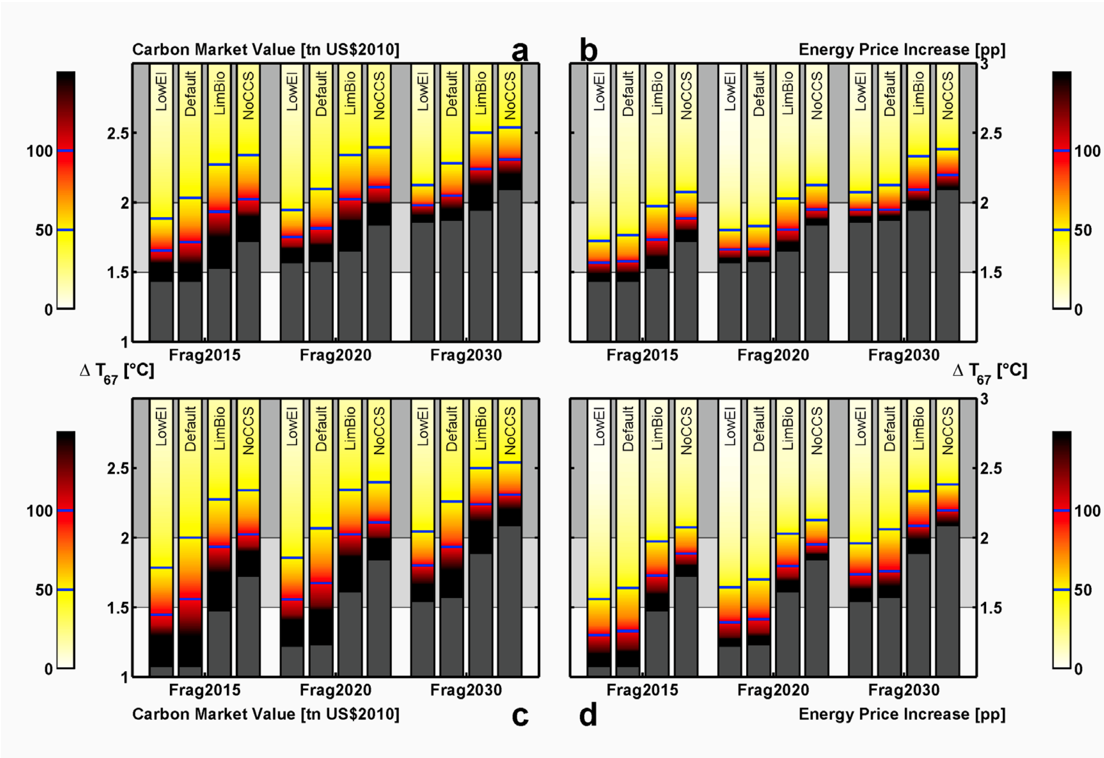

Figure S7: Overview of the combined effects of mitigation timing and technology availability on achievability of not-to-exceed targets and 2100 temperature target that allow for temporary overshoot. Graphs show economic challenges (color shading) in terms of aggregated carbon market value (left panels a,c), and short-term energy price increase (right panels b,d), as a function maximal 2010-2100 temperature increase (upper panels) or 2100 temperature increase (lower panel). Dark grey areas at the base of bars indicate temperature target levels that were not achieved with the range of carbon price paths assumed.

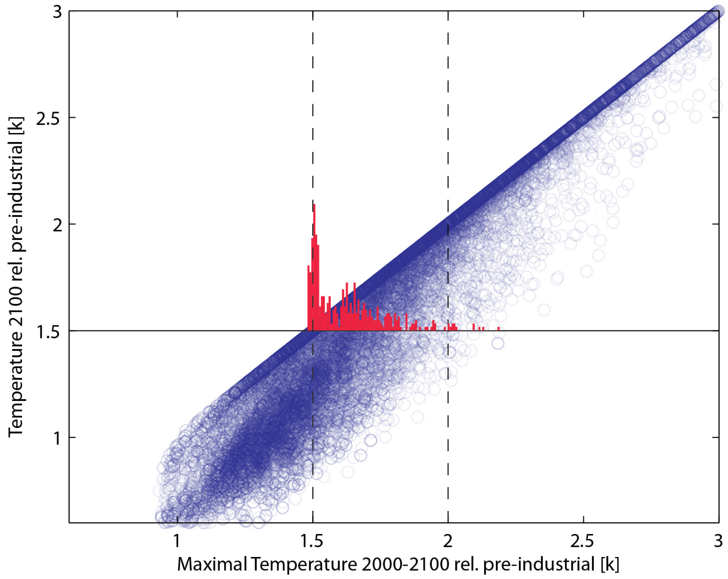

Figure S8: Relationship between maximum surface air temperatures during the 21st century (horizontal axis) and 2100 surface air temperatures (vertical axis) for the full set of 171,000 climate model realizations of the 285 REMIND scenarios. The red histogram shows the distribution of maximal 2000-2100 temperatures that result in a temperature of 1.5°C in 2100.

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