SUPPLEMENTARY INFORMATION

doi:10.1038/nature11787

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1. MODELLING FRAMEWORK

1.1 Integrated Assessment Model (IAM): MESSAGE

Our ensemble of technologically and economically consistent global emission scenarios is created with the integrated assessment modelling (IAM) framework MESSAGE[1,2]. It takes into account constraints on technology availability, technology diffusion rates, and limitation of resources, amongst other things[3]. MESSAGE also provides all of the cost information (carbon prices and mitigation costs) that are required to generate the cost distributions of this study. The MESSAGE model includes a detailed representation of the current global energy system (with regional disaggregation) and simulates possible future scenarios taking into account constraints on the availability of technologies and resources, penetration rates of technologies into the energy system, and future energy demand levels.

Here we vary both the technologies which are assumed to become available over the twenty-first century and the future levels of energy demand[3] (see Table 1 in the main text), resulting in a total of 17 future technology portfolio-demand combinations (Supplementary Table S1). Technological availability is varied in ways that make long-term mitigation both easier (advanced transportation, advanced non-CO_2 mitigation) and more difficult (no new nuclear, limited land-based measures, no CCS). Likewise, demand trajectories – for each of the MESSAGE models eleven world regions – are varied from the intermediate level to both a higher and a lower level. A detailed description of the scenario assumptions is given in Ref. 3 or below.

Within each of the 17 overarching technology portfolio-demand categories, an ensemble of roughly 30 scenario runs is created (Supplementary Table S1) by imposing increasingly stringent cumulative greenhouse gas (GHG) budgets for the twenty-first century. These budgets include all GHGs and are expressed in terms of carbon-dioxide equivalent emissions[4]. GHG mitigation hence affects all GHGs in our scenarios. Each ensemble ranges from a reference scenario without climate policy to a scenario in which the feasibility threshold of the model is reached (Supplementary Figure S1). A scenario is considered infeasible in our analysis if the net present value of the 2020 carbon price (discounted back to 2012 using a 5% real interest rate) exceeds 1,000 US\$/tCO_2e, a definition that we adopt from the recent international modelling intercomparison exercise of the Energy Modeling Forum 22 (EMF 22, Ref. 5).

MESSAGE is an inter-temporal optimisation model with perfect foresight. As with other macro-economic and systems-engineering models with foresight (e.g., MERGE[6], ReMIND[7], TIAM[8]), the carbon price in a specific mitigation scenario increases over time with the discount rate. This is because of the cumulative nature of the climate problem and the optimal weighting of the mitigation effort over time. The initial carbon price in our framework is thus also a good proxy for the carbon price in future periods. A carbon price of 10 US\$/tCO_2e in 2012, for instance, will at 5% interest grow to 15 US\$/tCO_2e by 2020, 64 US\$/tCO_2e by 2050, and 732 US\$/tCO_2e by 2100. While most readers might have a more intuitive feeling for carbon prices, the relationship between the probability of temperature targets and mitigation costs can be illustrated with a wide range of other cost metrics, such as total investments, changes in gross world product and consumption, or additional energy-system costs – most of which tend to be on the order of billions of dollars globally in scenarios with temperature limits of 2°C. For example, Supplementary Figures S2 and S3 show the cost-probability relationship for a 2°C target, using total mitigation costs relative to a baseline in the absence of climate policies, and as a percentage of gross world product (GWP) as the cost metric, respectively.

In addition to GHGs, MESSAGE tracks emissions of a full basket of air pollutant species from the energy, industrial and non-energy sectors of the economy (disaggregated at each of the models eleven regions[9]): particulate matter (PM2.5), sulphur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOC), carbon monoxide (CO), black carbon (BC), organic carbon (OC), and ammonia (NH_3). Most of these species are also short-lived climate forcers (SLCFs) due to the impacts they have on the global and regional climate (particularly over near-term timeframes), and can have an important impact on the temperature trajectory[10]. Ultimately, however, CO_2 remains by far the main contributor to peak warming[10]. Because climate policies will motivate efficiency improvements and the substitution of fossil-fuel technologies with renewables, SLCFs will likely decrease across the board as well[11-13], due to the tendency of low-carbon technologies to emit low or zero levels of air pollutants. This will have mixed effects on global temperatures, as some SLCFs cause warming (e.g., BC) and others (e.g., SO_2) cooling. To account for these mixed climate effects, we assess each scenario individually in terms of its projected temperature increase with a probabilistic climate model (see below).

1.2 Probabilistic Climate Model: MAGICC

Carbon-cycle and climate-system uncertainties have been quantified in the past through large-scale model intercomparison projects[14,15] and in the latest assessment of the Intergovernmental Panel on Climate Change[4] (IPCC AR4). The carbon-cycle uncertainty influences how global GHG emissions are translated into increased atmospheric GHG concentrations, while the climate-system uncertainty influences the temperature resulting from these increased concentrations. We use a probabilistic climate model MAGICC[16] which closely reflects these uncertainties in carbon cycle, climate system and climate sensitivity[17-19] as assessed by the IPCC AR4 (Ref. 4), and is constrained by historical observations. By doing so we reflect the state-of-the-art knowledge on the uncertainties in the global annual mean temperature response to anthropogenic GHG emissions.

In particular, we draw 600 parameter sets for the model from a large 82-dimensional joint distribution of climate and radiative forcing parameters[18], affecting the transient response in such a way that the marginal climate sensitivity distribution matches a distribution which is consistent with the climate sensitivity uncertainty assessment by the IPCC AR4 (i.e. 'likely' (>66%) between 2 and 4.5°C, 'very likely' (>90%) above 1.5°C, and most likely values around 3°C, see Ref. 19). Prior distributions for radiative forcings reflect the year 2005 uncertainty distributions following Table 2.12 in Ref. 20. Additionally, we apply observed hemispheric land/ocean temperatures[21] and observed ocean heat uptake estimates[22] as historical constraints, as described in Ref. 18. Future carbon-cycle uncertainties are reflected in addition to the historically constrained climate response parameters by applying one of 9 C^4MIP carbon-cycle model emulations at random.

"Pre-industrial" temperature values in this study are computed relative to the commonly used 1850-1875 base period.

1.3 Cost distribution methodology

For each scenario generated by the MESSAGE model, the probability that global temperature increase remains below a certain limit relative to pre-industrial levels is estimated with the probabilistic setup of the MAGICC model described above. Matching the mitigation cost estimates from the MESSAGE runs with the probabilistic temperature outcomes of the MAGICC runs for an entire ensemble of emission pathways provides us with a distribution of costs versus probability consistent with a given global temperature target, for example 2°C. Utilizing this straightforward, transparent procedure, cost-probability distributions, as seen in Figure 2 of the main text, are created for each of the 17 technology portfolio-demand combinations mentioned earlier. We generate these distributions for a global temperature limit of 2°C (Figure 2 of the main text), 2.5° (Supplementary Figure S4), and 3°C (Supplementary Figure S5), and also look at the probability to return warming to below 1.5°C by 2100 (Figure 3 in the main text).

To model the influence of delayed global mitigation action, the MESSAGE model has been run in a two-stage setup, as described previously in Ref. 23 and 24. In the first stage, the model is run myopically without a climate policy constraint for one or two periods, for example until 2020 or 2030. Consequently, the evolution of the energy system up to that period is frozen, and the model is restarted from its base year, now with full knowledge of a long-term constraint on cumulative GHG gas emissions (in terms of carbon dioxide equivalent emissions over the entire twenty-first century).

1.4 Modelling framework limitations

The modelling tools that we use in this study are state-of-the-art in their field of science. As with any other modelling framework they use simplifications to represent complex interactions in the real world. In this section we summarise some of the limitations of the tools that are relevant for the interpretation of our results.

Energy system model Our energy-system model MESSAGE contains a detailed representation of the global energy system. This representation includes vintaging of the long-lived energy infrastructure (which allows for consideration of the timing of technology diffusion and substitution), the inertia of the system for replacing existing facilities with new generation systems, clustering effects (technological interdependence) and possible phenomena of increasing returns (i.e., the more a technology is applied the more it improves and widens its market potentials). These representations and relationships draw from historically observed, empirical trends and might therefore not be able to capture major societal paradigm shifts beyond those explicitly assumed in our analysis (for example, massive shifts toward technical and behavioural changes to limit energy demand in the "low demand cases").

Furthermore, while our sensitivity cases span a wide range, they are not exhaustive of all possible future outcomes. Both cases in which mitigation would be more difficult or would become easier can be imagined. Consistent with the great majority of the IAM literature[25], we consider in our analysis a wide portfolio of technologies that are either commercially available today or have proven their feasibility at laboratory stage. Other future technological breakthroughs, such as for example nuclear fusion, solar power satellites or geo-engineering approaches to climate mitigation, are not taken into account. Similarly, other technology or policy failures over and above the specifically modelled cases of unavailability of certain technologies and globally-delayed mitigation action have not been explored. The full space of possible energy futures might thus be larger than explored by our analysis.

Similar to other global long-term integrated assessment models, our modelling framework (MESSAGE) has limitations with respect to its coarse decadal temporal resolution, i.e., the model solves an inter-temporal optimization problem using ten year time steps from 2010 onwards. Intermediate results between these time-steps (for example, for 2015 and 2025 in Figure 2) have been constructed for illustrative purposes, and are thus less robust than direct model outcomes for the decadal increments. In particular, for the delayed action scenarios until 2015 (2025), emissions growth was limited between 2010 and 2020 (2020 and 2030) in a way such that emissions in 2020 (2030) are equal to emissions in 2010 (2020). As explained further above, the delayed actions scenarios were run in two stages. First the evolution of the energy system up to 2020 (2030) is frozen, and the model is restarted with full knowledge of the long-term constraint on cumulative GHG gas emissions. Essentially this approach assumes that any increase in emissions in the first 5 year increments (for example, 2010-2015) could be offset by mitigation in the second 5 year period (for example, 2015-2020). This behaviour is broadly consistent with the dynamics of the delayed action scenarios based on direct model outcomes given an intermediate future energy demand level and 10 year delays. Although this approach allows to gain some insights on the sensitivity of the results to a gradually increasing delay of mitigation action, the cases with delayed action until 2015 and 2025 provide less robust a result than the immediate action cases and the 2020 and 2030 delayed action cases.

Costs of mitigation and avoided impacts The reported costs in our model are either energy system costs or total mitigation costs. Total mitigation costs include energy-related investments, operation and maintenance (O&M) costs, fuel costs, demand-side efficiency costs, and non-energy mitigation costs, and are computed relative to the total system costs of the baseline scenario without climate mitigation (and with availability of the full technology portfolio). However, they do not consider the benefits of avoided climate impacts. Our assessment follows thus the traditional cost-effectiveness approach, whereas the temperature limit (2°C, 1.5°C, or any other value) is an exogenous constraint translated into a cumulative GHG emission budget over the twenty-first century. Based on this (and other physical and techno-economic) constraint(s) MESSAGE determines the least-cost energy-economic transformation pathway to achieve the required greenhouse gas emissions reductions.

Relationship of carbon prices and cost of mitigation In the main text we report primarily on the carbon price in 2012 as a metric to express the stringency of mitigation action required to meet long-term climate goals with a given probability. While this may be the most relevant metric from a policy perspective, since it represents a variable that policy can actively influence, other metrics such as total mitigation costs are also of relevance. Supplementary Figure S10 therefore shows the relationship between 2012 carbon prices and mitigation costs in our scenarios. We find a robust relationship for scenarios with similar level of energy demand with some variation of that relationship across the different energy demand levels. Supplementary Figures S2 and S3 further show our main results for other cost metrics, including total mitigations costs as well as the total mitigation costs as a fraction of GDP and their relationship to probabilities for achieving long-term goals. Both metrics are useful for exploring the relative influence of technology assumptions and political choices with that of energy demand. Most importantly, the relative importance of the different geophysical and socio-economic uncertainties explored in this study remains the same across all cost metrics that we explored.

Immediate action 'Immediate action' scenarios assume that mitigation action scales up from zero in 2010 to a certain value in 2020. Our model results can therefore not inform us about precisely how much mitigation action is assumed to be already in place by now (i.e., 2012). Only with the passing of time will it become clear which global carbon price in 2020 would be consistent with the level of mitigation action until then.

Discount rate Model assumptions about discount rates are closely associated with assumptions about the social cost of capital, which reflects the opportunity cost of alternative investments and sets the real growth rate of the carbon price in an intertemporally-optimising model like MESSAGE. We assume a discount rate (or social cost of capital) of 5% in our model runs, consistent with that used for scenario analyses by the IPCC[25]. However, a lively debate about the discount rate exists, and it has been argued that a lower discount rate might be more appropriate for long-term problems like climate change[26]. A sensitivity analysis of our results to the choice of discount rate indicates that although the relative importance of uncertainties is probably maintained, carbon prices shift to higher near-term values for lower discount rates and the same probability of achieving the 2°C objective (Supplementary Figure S6). The fact that the shape of our distributions does not change is related to the setup of our analysis. If our analysis would have performed a cost-benefit analysis of the cost of climate mitigation versus avoided impacts, the choice of discount rate would most likely also change the shape of our distributions. However, as described earlier, each scenario in our sets has a prescribed cumulative GHG emissions budget for the twenty-first century. A change in the discount rate (or social cost of capital) in our model will therefore not influence the pertinence of GHG mitigation, but rather only the timing of it.

Climate model To incorporate state-of-the-art uncertainty quantifications of the Earth system's response to GHG emissions, the setup of our climate and carbon-cycle model MAGICC draws its knowledge from the available scientific literature in the field and from studies published by significantly more complex atmosphere ocean general circulation models (AOGCMs) and carbon cycle models. In particular, the setup we use has been developed to closely represent the assessment of uncertainties by the IPCC AR4 (Ref. 19). However, tipping points of the climate system at higher levels of warming remain currently underexplored in that body of literature. Also our climate model does therefore not incorporate or emulate such behaviour. While our core results with regard to the relative importance of geophysical, technological, social, and political uncertainties are likely to be robust, specific values of costs and related exceedance probabilities will change together with the advancement of scientific understanding of the climate system.

2. SENSITIVITY CASES DESCRIPTIONS

2.1 Detailed descriptions

A large set of sensitivity cases was created to explore how technological and social uncertainties, as well as political choices, influence our distributions. A first aspect that is varied in our sensitivity cases is the availability of key mitigation technologies. We implement both technology-limiting cases and technological breakthroughs, which make the mitigation of GHGs respectively more difficult and easier. Our three technology-limiting cases ("no new nuclear", "limited land-based measures", and "no CCS") are implemented as the "No nuclear", "Limited bio-energy", and "No CCS" cases, respectively, described in Chapter 17 "Energy Pathways Towards Sustainable Development"[3] of the Global Energy Assessment[1]. Of our two technological breakthrough cases, a first ("Advanced transportation") is also described in detail in Ref. 3. A second technological breakthrough case ("Advanced non-CO_2 mitigation") was developed by the authors of this study and first described in Ref. 27.

To model the non-CO_2 mitigation potential, we use abatement cost curves based on work from Beach and colleagues[28]. In the default case, a standard set of cost curves is used, which reflect non-CO_2 mitigation potentials for the year 2020. They assume no further technological improvements after 2020. The fraction of agricultural emissions that can be mitigated does therefore not change over time. Although possible, this corresponds to a rather conservative interpretation for the long-term potential. Our "Advanced non-CO_2 mitigation" case explores the sensitivity of our results to this assumption and assumes a continuous improvement of the non-CO_2 mitigation potential from 2020 to 2050, and at lower rates out to 2100 (with rates described in Ref. 29). In particular, the improvement rates from 2020 to 2050 for (i) N_2O emission from soils and CH_4 from enteric fermentation, for (ii) CH_4 emissions from paddy rice, for (iii) CH_4 emissions from manure, and for (iv) all other emissions are 3.9%, 1.5%, 2.4%, and 0.4% per annum, respectively. Given the uncertainties and the simple assumptions made, our "Advanced non-CO_2 mitigation" case should be solely used in the framework of a sensitivity analysis of our results. It does not attempt to project the maximum attainable non-CO_2 mitigation potential for any specific technology[29].

The supply-side sensitivity cases (see Table 1 in the main text and Supplementary Table S1) model how societal choices to put more or less emphasis on energy efficiency improvements will result in a low, intermediate, or high future energy demand future. They are based on the GEA-Efficiency, GEA-Mix, and GEA-Supply scenario families from the Global Energy Assessment, respectively. Detailed background information on these scenario families is provided in Ref. 3.

To model the influence of delayed global mitigation action, the MESSAGE model has been run in a two-stage setup, as described previously in Ref. 23 and 24. In the first stage, the model is run myopically without a climate policy constraint for one or two periods, for example until 2020 or 2030. The model has no knowledge of a possible future constraint on GHG emissions (hence, it is named "myopic"), and will do no effort to reduce or limit

[1] http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/Home-GEA.en.html

emissions during this first stage. Consequently, the evolution of the energy system up to that period is frozen, and the model is restarted from its base year, now with full knowledge of a long-term constraint on cumulative GHG emissions (in terms of CO_2 equivalent emissions over the entire twenty-first century). It will now optimize the energy system for the rest of the century in order to comply with the cumulative constraint on GHG emissions, starting from the higher emissions in 2020 or 2030.

2.2 Different drivers of future energy demand and GHG emissions

The evolution of future energy demand can be decomposed into three main drivers, following a variation of the Kaya identity[30]: $E_d = P.GDP.EI$ with energy demand (E_d) dependent on population (P), gross world product per capita (GDP), and energy intensity (EI, for example in primary energy per GDP). In our scenarios, we apply population and GDP projections based on an updated SRES B2 scenario (see Methods in the main article and Ref. 3). The distinction between our energy demand cases is solely driven by varying assumptions on energy intensity evolutions in the society. Projections of population and GDP are not varied across our three future demand cases. We follow this approach to fully explore the influence of uncertainties related to possible evolutions of the energy system, irrespective of uncertainties in population and economic growth projections. Had we in fact varied our population and GDP assumptions, then this would have influenced our results. Therefore, a comparison of the characteristics of our demand sensitivity cases (see earlier) to evolutions found in the SRES marker scenarios[31] can provide valuable context for the framing of our scenarios.

Global total final energy demand in 2100, for instance, varies around our central intermediate demand (reference) case by +32% to -37% for our high and low energy demand cases, respectively. In the SRES scenarios, we find a maximum variation of -62% to +64% around our reference case, for the SRES B1 and SRES A1 scenario, respectively. Most interestingly, the A1 and B1 scenarios that span the range of energy demands in the SRES are based on the same population trajectories. They differ however in major ways with respect to the underlying assumption with respect to technological change (driving energy intensity) and economic growth. Looking more in depth in these two extremes shows that both B1 and A1 assume a *higher* GDP per capita in 2100 than in our scenarios (about 67 and 169% higher, respectively). In terms of energy intensity in 2100, both scenarios are however -70 and -18% *lower* than our reference case, respectively. For comparison, in our three demand cases energy intensity varies about -39 to +36% around our reference case.

The full range of energy demand in the SRES scenarios is thus due to a combination of different drivers. The drivers do not translate in a straight-forward or linear way into high or low energy demand, but their effects often offset each other. This is also illustrated by the fact that very different assumptions for the combination of GDP and population drivers can lead to similar energy demands as shown, for example, by the full ensemble of the SRES scenarios.

To better understand how much of the scenario space is covered by our projections, we compare the range of CO_2 and GHG emissions of our three baseline scenarios with the ranges from recently updated SRES scenarios[1]. The comparison is important since some combinations of drivers are less likely than others, and the SRES process aimed at covering the uncertainty range of baseline emissions through systematically exploring plausible combinations of GDP, population and technology drivers. As illustrated by Supplementary Figure S7, the baseline scenarios in our assessment span about 75% of the uncertainty range of GHG emissions from the SRES scenario families from A2 down to B1. The combination of assumptions in our cases thus spans a range of emissions similar to other studies that have systematically explored alternative combinations of socio-economic drivers of emissions, including population, GDP, and technological change. Despite the wide range, an important caveat is, however, that our baselines do not fully represent the lower bound of the emissions range from SRES. This might indicate that in some cases mitigation costs might have been lower if we had also explored the sensitivity of our results with respect to varying GDP and population assumptions.

Finally, Supplementary Figure S8 provides a comparison of our results with the recent EMF 22 scenarios[5] coded as a function of (1) their proximity to our GDP and population projections (Supplementary Figure S8a), and (2) their trends of future energy demand and their timing of mitigation action (Supplementary Figure S8b).

3. RELATIVE IMPORTANCE OF UNCERTAINTIES

We here report how the relative importance of geophysical, technological, social (energy demand-related), and political uncertainties has been derived in this analysis. Based on the assessment with our model, we find that delayed mitigation has the largest effect on the cost-risk distribution for 2°C, followed by geophysical uncertainties, social factors influencing future energy demand, and mitigation technology uncertainties. This relative importance can be different for other temperature objectives.

We assess the relative importance of the different factors primarily through how different assumptions for technical, social and political developments influence the geophysical uncertainty range. In the case of immediate action and intermediate demand, geophysical uncertainties result in a range of 70% for the probability to stay below 2°C, across all assessed carbon prices (see arrow 1 in Supplementary Figure S9 and Table S2). Delay in mitigation to 2030 compresses this geophysical uncertainty to only about 20% (arrow 5 in Supplementary Figure S9). Hence, a large part of the geophysical uncertainty is only present because of the assumption that there is no delay in action. We therefore consider that the political uncertainty dominates over geophysical uncertainties.

In order to assess the importance of social factors influencing energy demand and mitigation technology uncertainties, we explore how much of the spread in geophysical uncertainties changes by these factors. Alternative assumptions in these factors create a maximum shift in the geophysical uncertainty of 45% and 25%, respectively (Supplementary Table S2 and arrows 2 and 4 in Supplementary Figure S9). We thus conclude that social uncertainties affecting energy demand outweigh technology uncertainties. At the same time both uncertainties rank relatively lower than the overall geophysical uncertainty.

4. SUPPLEMENTARY TABLES

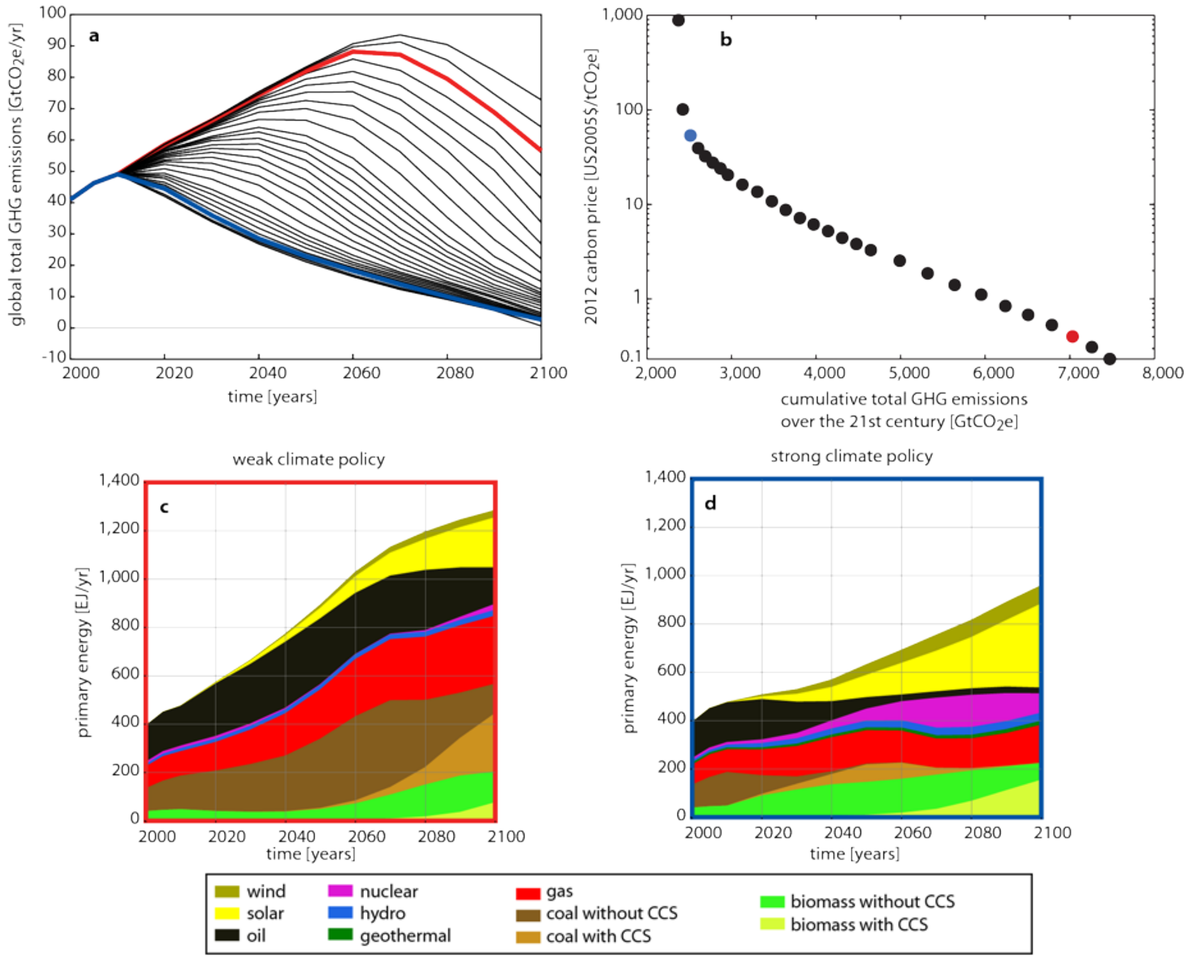
Supplementary Table S1 | Overview of 17 future technology portfolio-demand combinations. The values in the table indicate the number of scenarios per case. All cases for which we assume future energy demand to be "Low" already include a higher level of electrification of the transportation sector, see Ref. 3.

NUMBER OF SCENARIOS			
	Future energy demand sensitivity		
Mitigation technology sensitivity	*Low*	*Intermediate*	*High*
Full technology portfolio	33	29	31
No new nuclear	31	27	28
Limited land-based mitigation measures	31	25	27
No CCS	32	25	26
Advanced long-term non-CO_2 mitigation	36	32	34
Advanced transportation	Assumption included in all of the above low demand cases	32	33

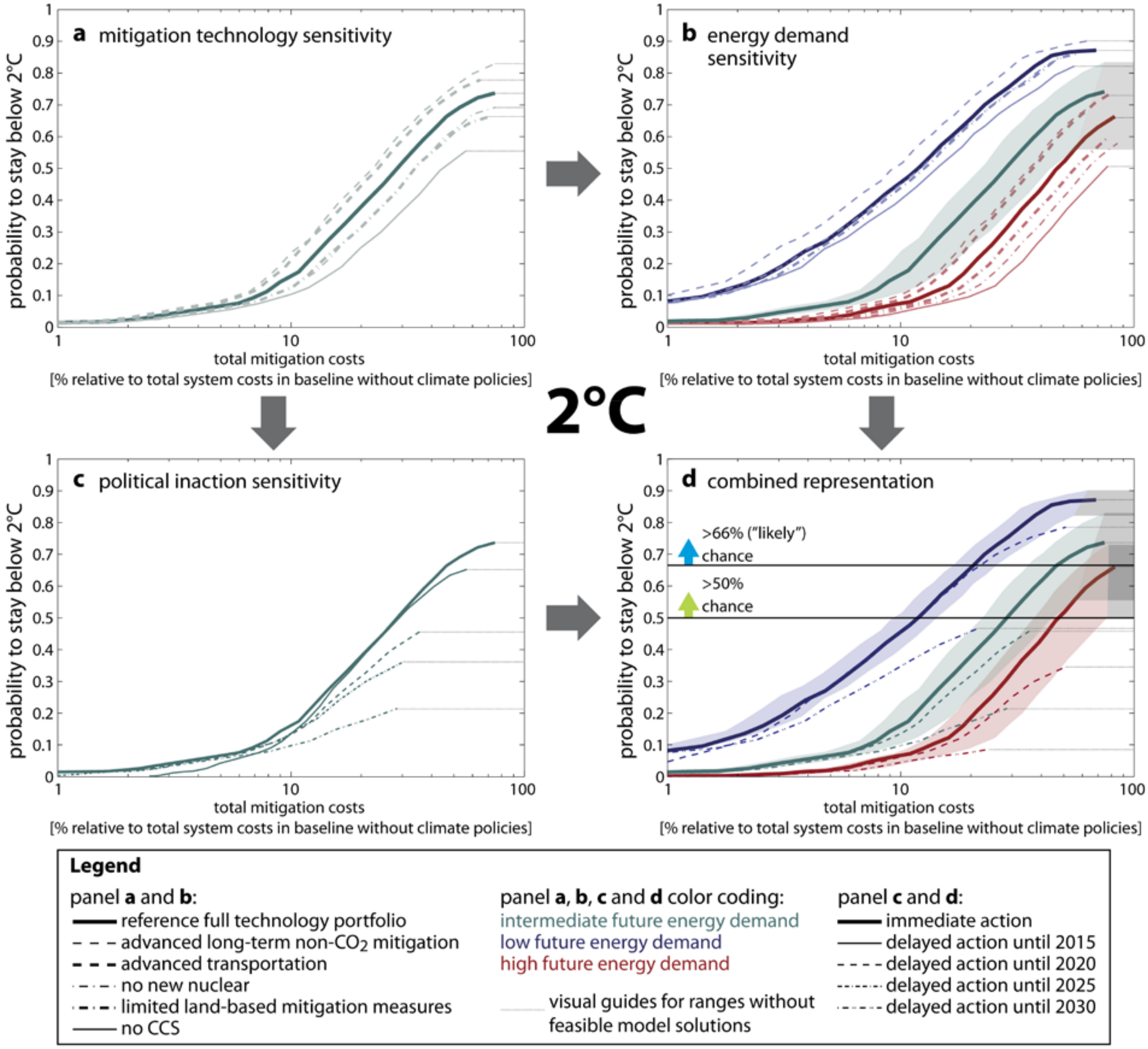
Supplementary Table S2 | Overview relative importance of uncertainties. Maximum influence on probability to limit global temperature increase to below 2°C. Percentage values represent the ranges indicated by the black vertical arrows in Supplementary Figure S9, and values between squared brackets indicate the arrow labels in Supplementary Figure S9. Probabilities are rounded to the nearest 5%.

Maximum influence on probability to limit global temperature increase to below 2°C	
Geophysical uncertainties	70% [1,3]
Technological uncertainties	25% [2]
Social uncertainties influencing energy demand	45% [4]
Political uncertainties (delayed mitigation action until 2030)	50% [6]
Geophysical uncertainties under delayed mitigation action	20% [5]
Technological uncertainties under delayed mitigation action	not assessed
Social uncertainties influencing energy demand under delayed mitigation action	40% [7]

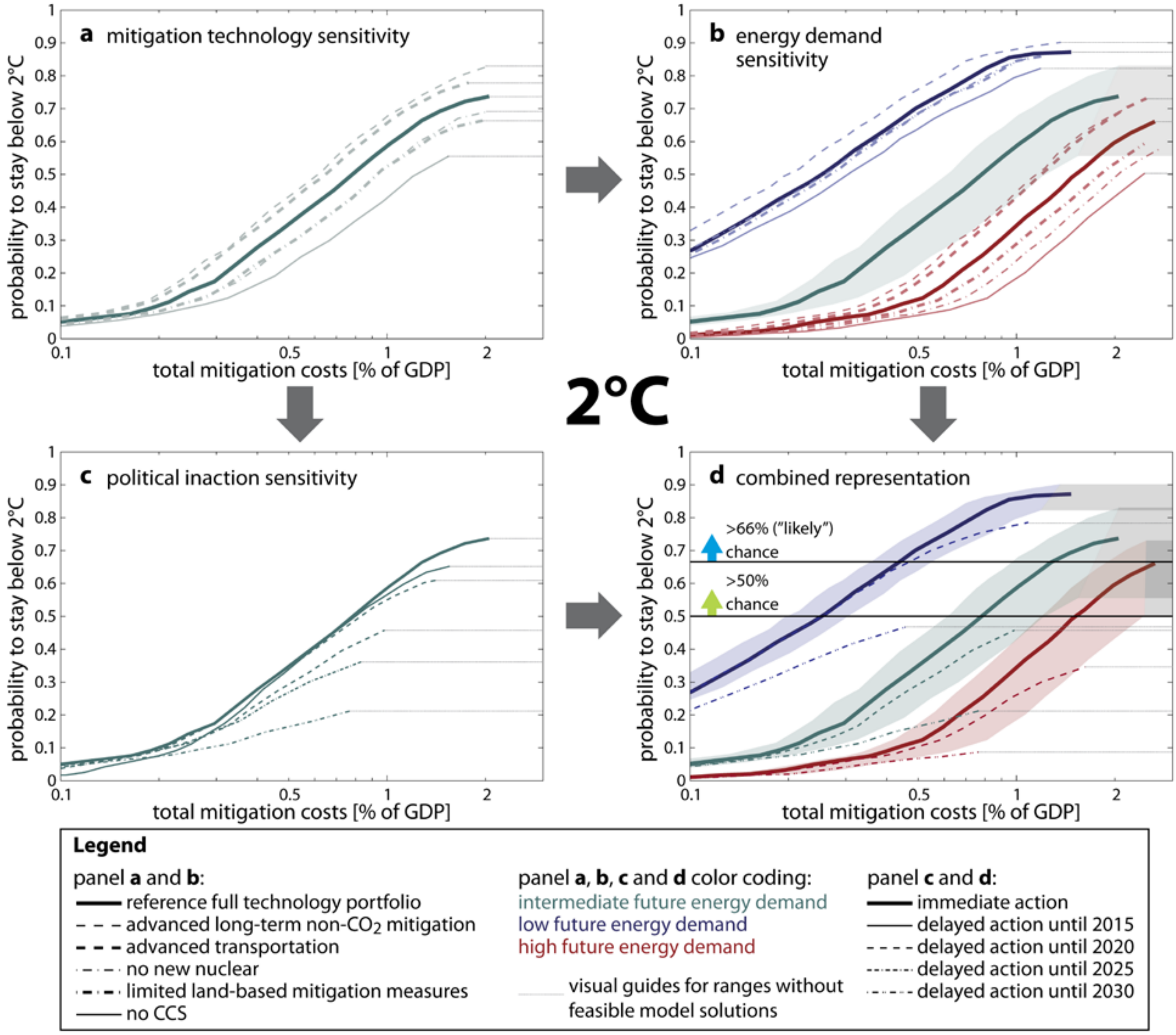
5. SUPPLEMENTARY FIGURES



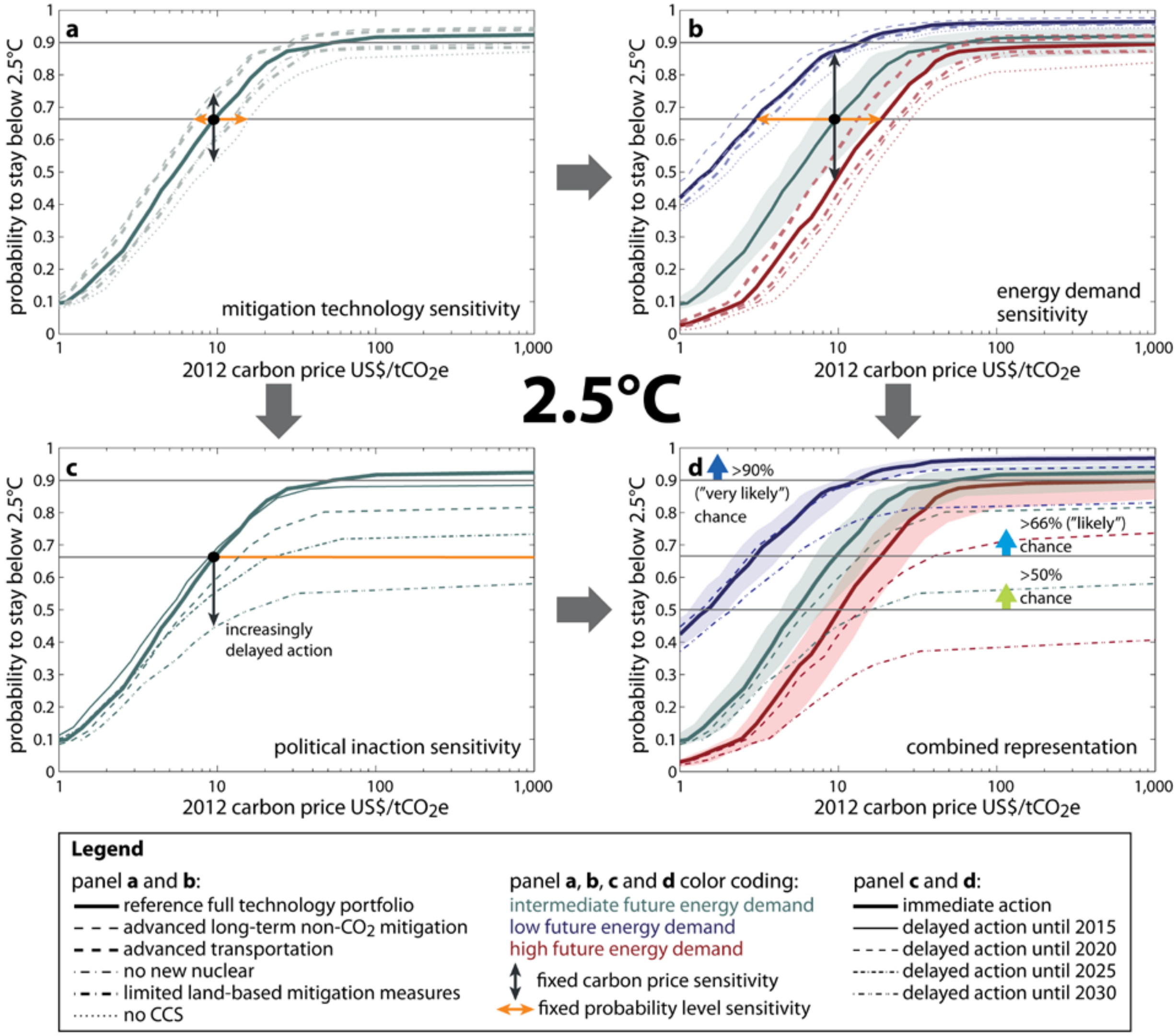
Supplementary Figure S1 | Illustration of a scenario set generated for this study. a, Emission pathways of one of the seventeen sets of scenarios (as described in Supplementary Table S1), ranging from scenarios without climate policies to scenarios where the feasibility threshold of the model is reached; **b**, Illustration of relationship between cumulative global GHG emissions over the twenty-first century and 2012 carbon prices for the illustrative scenario set in panel **a**; **c-d**, Illustrative energy system development with weak climate policy (panel **c,** corresponding to the red line in panel **a**) and with strong climate policy (panel **d**, corresponding to the blue line in panel **a**). The lower level in primary energy supply in panel **d** is due to efficiency measures both at the supply and demand side. Primary energy supply is computed following the direct equivalence method. The illustrative set shown here is the intermediate demand, full technology portfolio case.



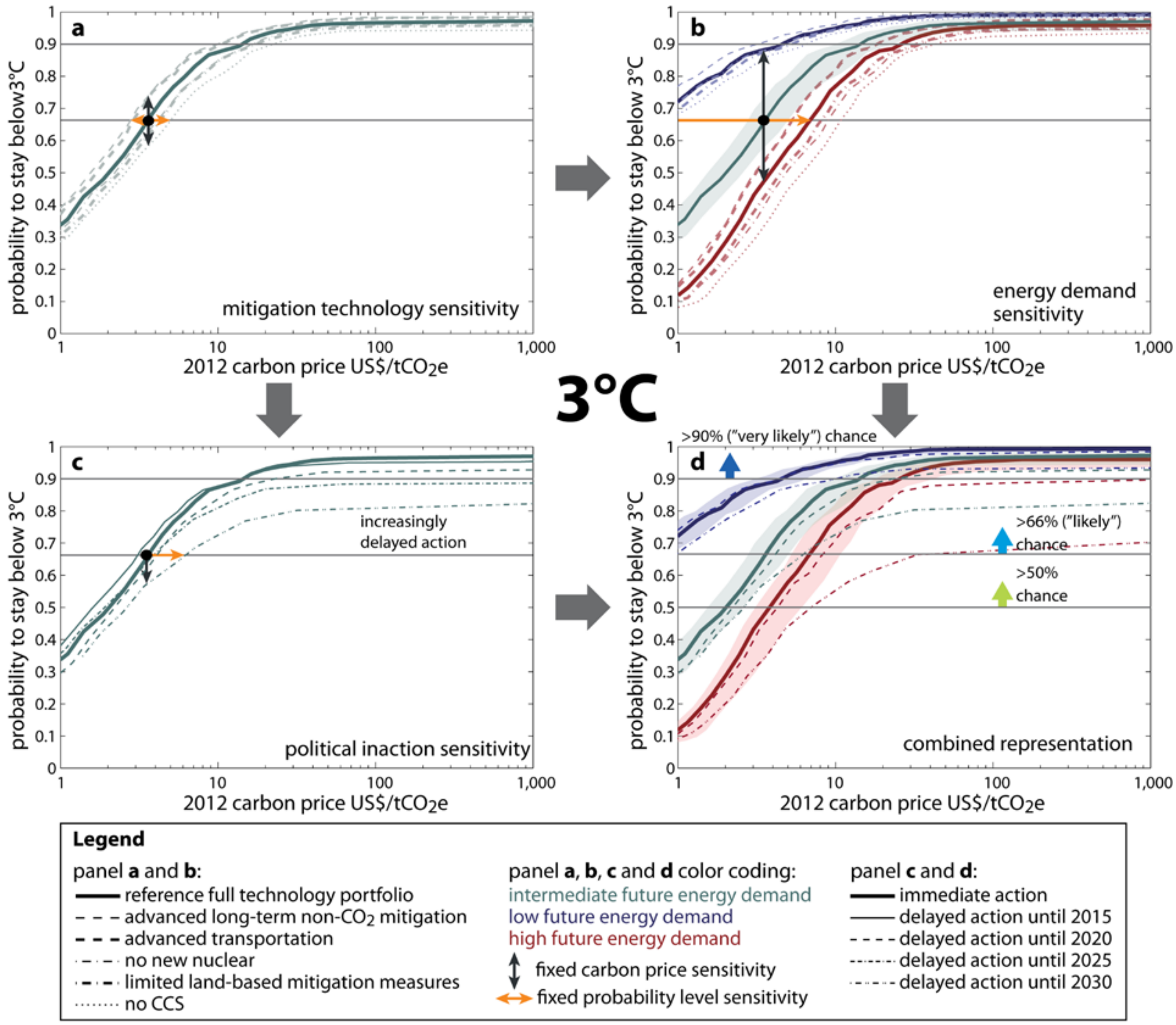
Supplementary Figure S2 | Cost-risk distributions of total discounted mitigation costs (2012-2100) for staying below 2°C. Total mitigation costs include energy-related investments, operation and maintenance (O&M) costs, fuel costs, demand-side efficiency costs, and non-energy mitigation costs, and are given as a percentage increase relative to the total system costs of the baseline scenario without climate mitigation (and with availability of the full technology portfolio). **a**, Cost distributions for six cases with varying future availability of specific mitigation technologies; **b**, Cost distributions for three energy demand sensitivity cases that yield various levels of future energy demand (thick solid lines). Shaded areas and dashed lines represent technology sensitivity cases comparable to those shown in panel **a**; **c**, Five cost distributions illustrating the impact of delaying global mitigation action; **d**, Overview figure combining the sensitivity cases of panel **a**, **b**, and **c**, together with probability thresholds of at least 50%, and at least 66%, to limit temperature increase to below 2°C. Dotted horizontal grey lines and grey ranges are visual guides for ranges of the distribution where no feasible scenarios are available (discounted 2020 carbon prices of the next scenario would exceed the feasibility threshold in our model of 1000 US$/t$CO_2$e in 2012).



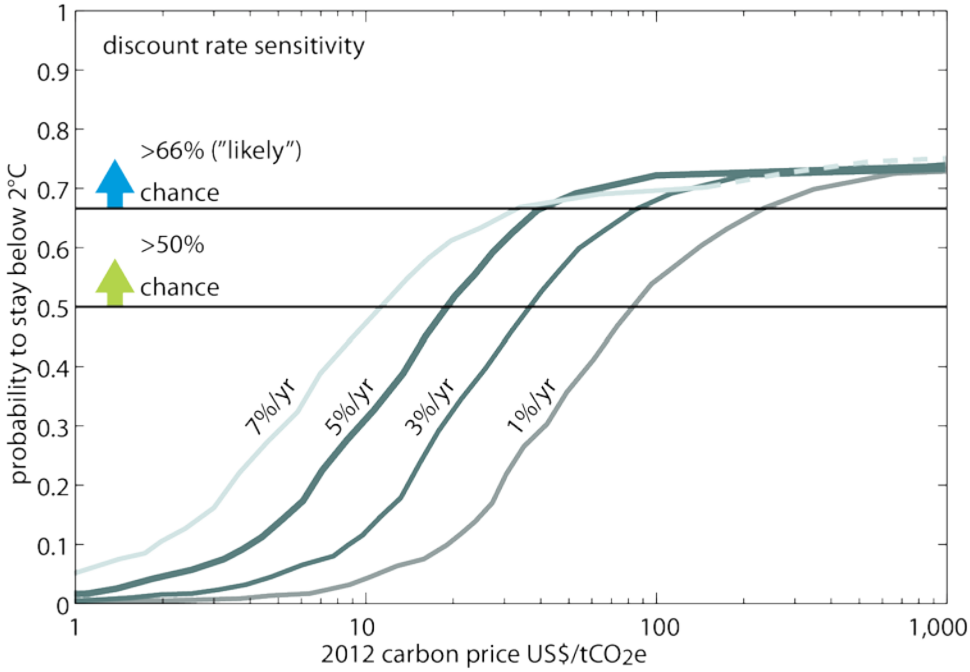
Supplementary Figure S3 | Cost-risk distributions of total discounted mitigation costs (2012-2100) as a fraction of GDP for staying below 2°C. Total mitigation costs include energy-related investments, operation and maintenance (O&M) costs, fuel costs, demand-side efficiency costs, and non-energy mitigation costs, are computed as the increase relative to the total system costs of the baseline scenario without climate mitigation (and with availability of the full technology portfolio), and are reported relative to Gross World Product (GDP). **a**, Cost distributions for six cases with varying future availability of specific mitigation technologies; **b**, Three energy demand sensitivity cases that yield various levels of future energy demand (thick solid lines). Shaded areas and dashed lines represent technology sensitivity cases comparable to those shown in panel **a**; **c**, Five distributions illustrating the impact of delaying global mitigation action; **d**, Overview figure combining the sensitivity cases of panel **a**, **b**, and **c**, together with probability thresholds of at least 50%, and at least 66%, to limit temperature increase to below 2°C. Dotted horizontal grey lines and grey ranges are visual guides for ranges of the distribution where no feasible scenarios are available (discounted 2020 carbon prices of the next scenario would exceed the feasibility threshold in our model of 1000 US$/t$CO_2$e in 2012).



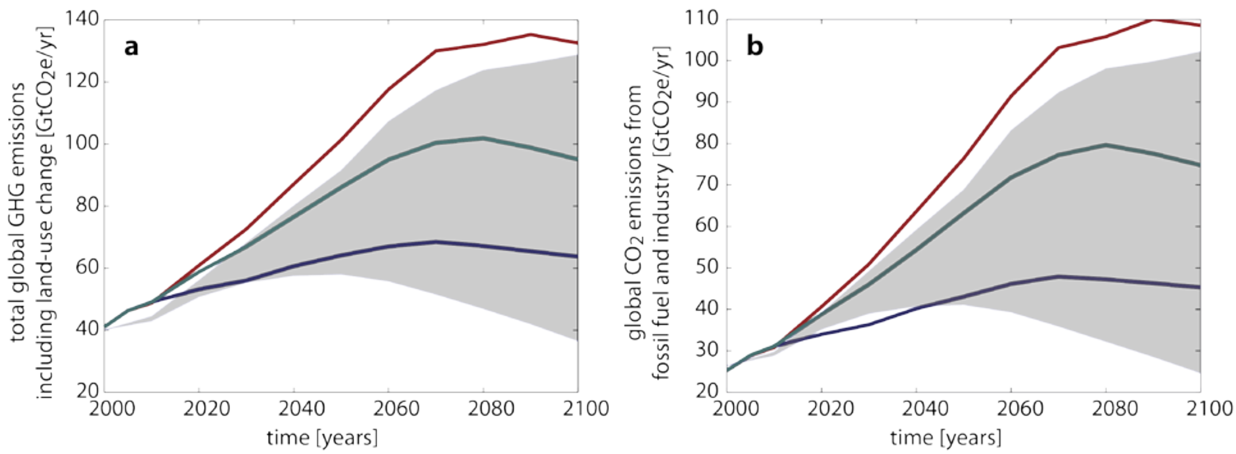
Supplementary Figure S4 | Analysis of influence of mitigation technology availability, energy demand, and political inaction on the mitigation cost distribution for staying below 2.5°C. Cost distributions for six cases with varying future availability of specific mitigation technologies (panel **a**), and three sensitivity cases for future energy demand (panel **b**, thick solid lines). Shaded areas and dashed lines in panel **b** (**d**) represent technology (technology and political) sensitivity cases comparable to those shown in panel **a** (**a** and **b**); **c**, Illustration of the impact of delayed global mitigation action; **d**, Overview figure combining all sensitivity cases. The horizontal lines in panels **a**-**c** are the 66% and 90% lines, respectively.



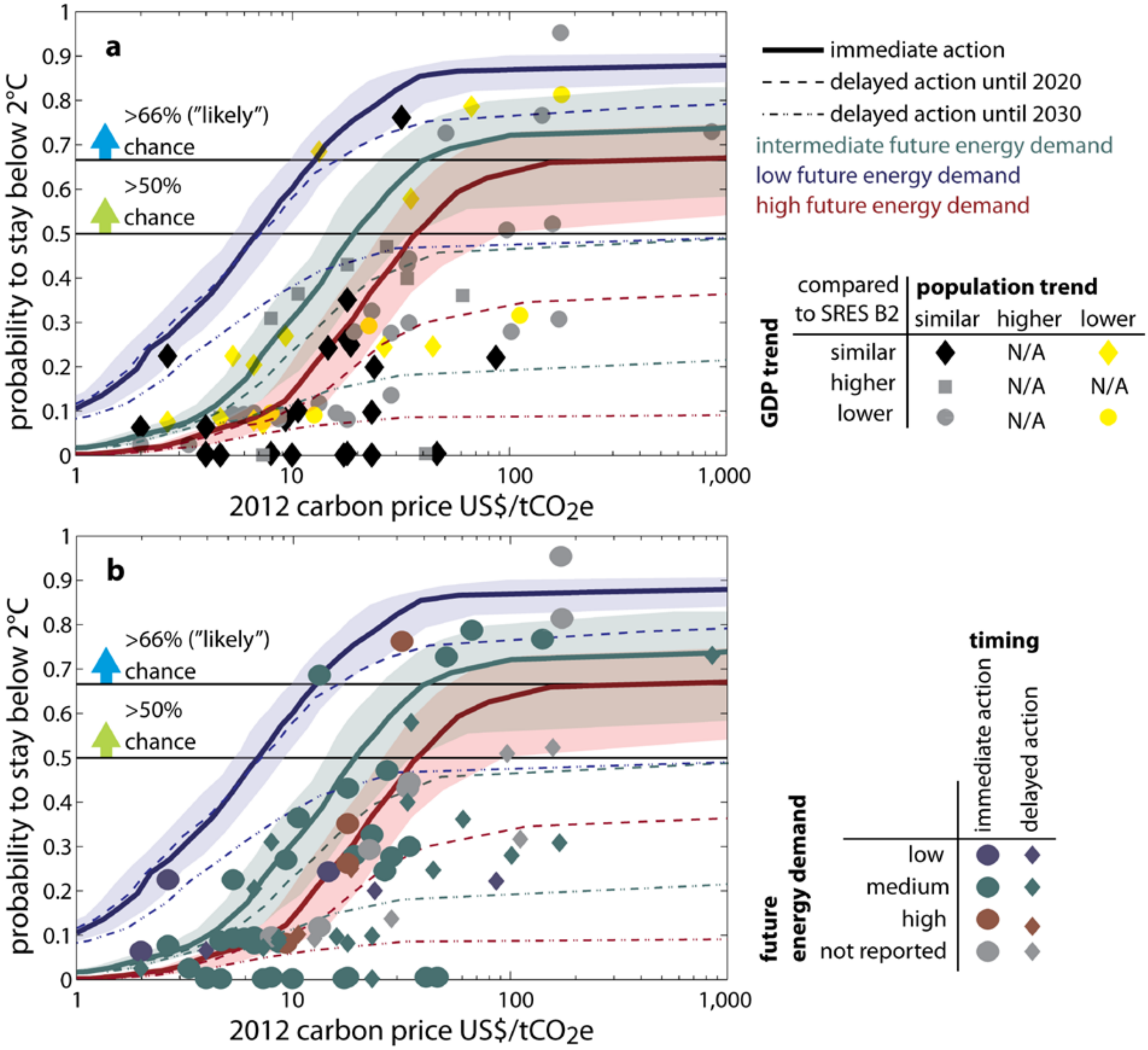
Supplementary Figure S5 | Analysis of influence of mitigation technology availability, energy demand, and political inaction on the mitigation cost distribution for staying below 3°C. Cost distributions for six cases with varying future availability of specific mitigation technologies (panel **a**), and three sensitivity cases for future energy demand (panel **b**, thick solid lines). Shaded areas and dashed lines in panel **b** (**d**) represent technology (technology and political) sensitivity cases comparable to those shown in panel **a** (**a** and **b**); **c**, Illustration of the impact of delayed global mitigation action; **d**, Overview figure combining all sensitivity cases. The horizontal lines in panels **a**-**c** are the 66% and 90% lines, respectively.



Supplementary Figure S6 | Sensitivity of the results to the discount rate. Three sensitivity cases for our intermediate demand, reference, full technology portfolio case are shown for a discount rate of 1, 3, and 7%/yr, respectively. The dashed part of the "7%/yr" distribution represents scenarios that are considered infeasible because of an excessively high share of backstop technology penetration (>5% of final energy by the end of the century). Note that the discount rate is closely related to the social cost of capital.

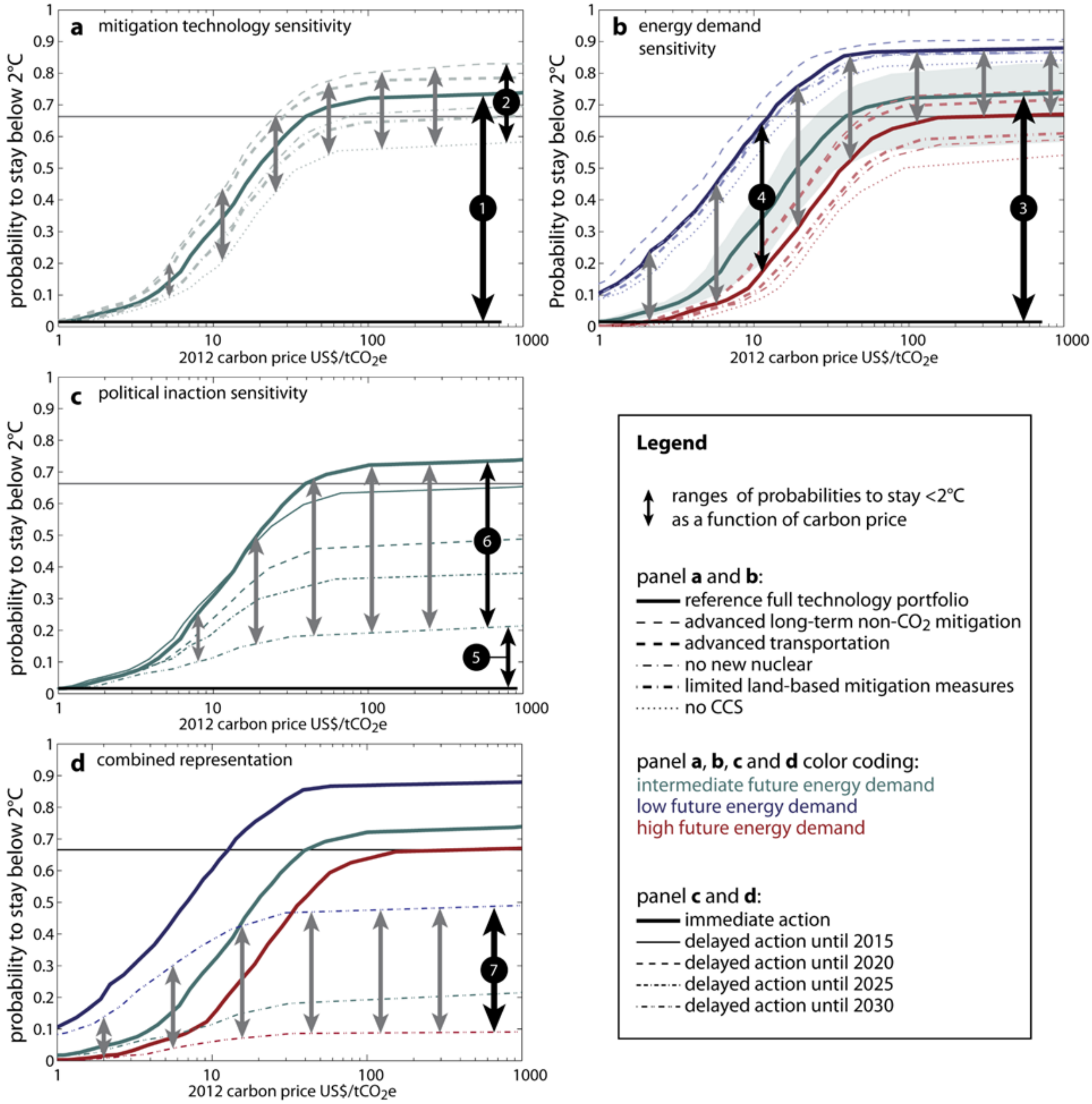


Supplementary Figure S7 | Comparison of emissions of the baseline emissions from our three future energy demand sensitivity cases and the full range of SRES no-mitigation scenarios. Lines represent global total greenhouse gas emissions (panel **a**) and CO_2 emissions from fossil fuels and industry (panel **b**) resulting from our three future energy demand sensitivity cases and assuming no climate policies. Blue, green, and red lines indicate a low, intermediate and high future energy demand, respectively. Grey shaded ranges show the range of emissions of the updated SRES scenarios as described in Ref. 1, and available online from http://www.iiasa.ac.at/web-apps/ggi/GgiDb/.

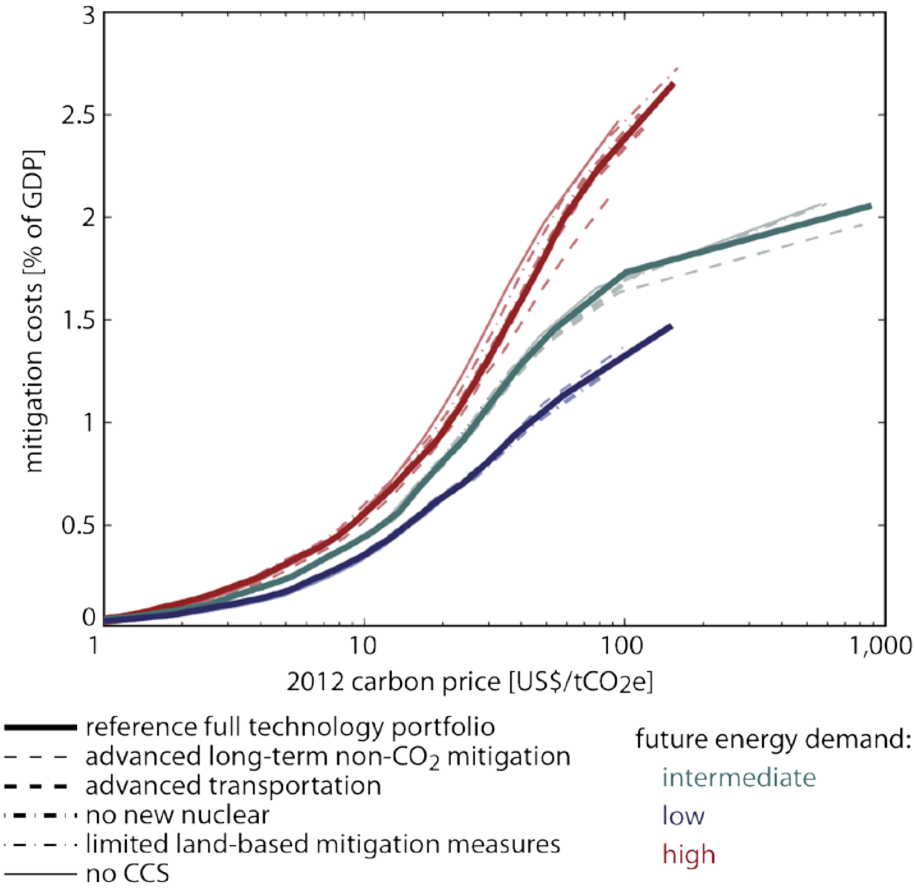


Supplementary Figure S8 | Illustrative comparison of our cost distributions with 91 scenarios from the literature. Lines represent the same data as Figure 2d in the main text. Each diamond, square, or circle represents one of the 91 "EMF 22 International Scenarios"[5], coded as a function of its proximity to the SRES B2 GDP and population trends (panel **a**) or as a function of its future energy demand and timing of action assumed in the scenario (panel **b**). Trends that lie within a 15% range around the original SRES B2 scenario are considered "similar". Cases that were not applicable are marked with "N/A". Shaded areas show the minimum maximum range of results per demand level for all technology cases considered. Exceedance probabilities have been computed with the methods described in Refs. 32 and 19.

The EMF 22 International Scenarios are the result from a large-scale integrated assessment modelling intercomparison involving eleven different international modelling teams. Carbon prices of the EMF 22 scenarios are approximated from available information on the price in the year 2020, using a discounted rate of 5%. Note that the discount rates might differ across EMF 22 scenarios and models and in some EMF 22 climate mitigation scenarios "without overshoot" carbon prices peak over the course of the century. The comparison is thus illustrative only, but shows the importance of carrying out comparable studies with other modelling frameworks.



Supplementary Figure S9 | Illustration of relative importance of uncertainties for staying below 2°C. Cost distributions for six cases with varying future availability of specific mitigation technologies (panel **a**), and three sensitivity cases for future energy demand (panel **b**, thick solid lines). Shaded areas and dashed lines in panel **b** represent technology sensitivity cases comparable to those shown in panel **a**; **c**, Illustration of the impact of delayed global mitigation action; **d**, Illustration of influence of social factors influencing energy demand in scenarios in which global mitigation action is delayed until 2030. The horizontal line in panels **a-d** is the 66% line. Vertical arrows indicate the ranges of probabilities to stay below 2°C as a function of a given carbon price. Black arrows show the maximum influence across all carbon prices from which the relative importance of geophysical, technological, social, and political uncertainties is derived. Grey arrows show illustrative other options. Values for the ranges are reported in Supplementary Table S2.



Supplementary Figure S10 | Relationship between carbon prices and total discounted mitigation costs (2012-2100) in our model. Relationships are shown for three different levels of future energy demand: low (blue), intermediate (green), and high (red). Mitigation costs include energy-related investments, operation and maintenance (O&M) costs, fuel costs, demand-side efficiency costs, and non-energy mitigation costs. They are calculated relative to the total system costs of the baseline scenario without climate mitigation (and with availability of the full technology portfolio) and are reported as a percentage of globally-aggregated gross domestic product (GDP).

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