Near-linear cost increase to reduce climate-change risk

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One approach in climate-change policy is to set normative long-term targets first and then infer the implied emissions pathways. An important example of a normative target is to limit the global-mean temperature change to a certain maximum. In general, reported cost estimates for limiting global warming often rise rapidly, even exponentially, as the scale of emission reductions from a reference level increases. This rapid rise may suggest that more ambitious policies may be prohibitively expensive. Here, we propose a probabilistic perspective, focused on the relationship between mitigation costs and the likelihood of achieving a climate target. We investigate the qualitative, functional relationship between the likelihood of achieving a normative target and the costs of climate-change mitigation. In contrast to the example of exponentially rising costs for lowering concentration levels, we show that the mitigation costs rise proportionally to the likelihood of meeting a temperature target, across a range of concentration levels. In economic terms investing in climate mitigation to increase the probability of achieving climate targets yields ''constant returns to scale,'' because of a counterbalancing rapid rise in the probabilities of meeting a temperature target as concentration is lowered.

abatement costs | climate targets | mitigation | probabilistic framework | risk approach

Attractive climate policy strategies may in theory be identified by balancing the costs of (avoided) climate change and adaptation against the costs of abatement (e.g., refs. 1 and 2). However, cost-benefit assessment of climate policy has been criticized. One reason is that cost-benefit analysis requires intertemporal and interregional equity considerations to be accounted for, because of uneven distributions of responsibility, cost, and benefits over time and space, implying implicit normative judgments (e.g., refs. 3–5). Significant uncertainties in estimates of damages and in the likelihood of abrupt changes in climate further complicate these assessments (6–8). In its Fourth Assessment Report the Intergovernmental Panel on Climate Change (IPCC) (9) concludes that it is not (yet) possible to "permit an unambiguous determination of an emissions pathway or stabilization level where benefits exceed costs."

An alternative approach to derive an overall target for climate policy is by seeking a cost-effective way to reach normative (risk-based) targets, such as the prevention of dangerous climate change (United Nations Framework Convention on Climate Change, Articles 2 and 3.3). Such targets can be defined with respect to potential climate impacts on, for example, ecosystems, food production, water, socioeconomic systems, and ice sheets (10). Global-mean surface–air temperature targets can be considered as proxies for the risk of adverse impacts from climate change (11–13). From a policy perspective, it is essential to have information on the probability of achieving such targets (14–17).

For both the cost-benefit approach and a risk-based approach, it is important to realize the dynamic nature of policymaking (18). Today's decision will need to be made in the face of many important long-term uncertainties and hedged against the risks associated with them (19, 20). Decisions will continuously be reevaluated against new information. There are important questions about how to relate long-term uncertainties to today's decision.

In this article, we will explore 2 crucial questions for climate-change policymaking based on a risk-oriented approach: (*i*) given a range of temperature-change targets, what is the probability of these being achieved under various greenhouse-gas concentration levels and (*ii*) what is the required mitigation effort, or cost, to increase the probability of achieving the temperature target?

For our calculations, we have opted for a set of simple equations, because these robustly capture the first-order characteristics of the problem. Our primary objective here is not to give quantitative results to base climate policy on, but to explore conceptually the qualitative nature of the link between the probability of achieving global climate-policy targets and the expenditure on emission reductions.

Our starting point is a normative target of long-term (equilibrium) change of global-mean temperature dT_{stab} (°C). This target is linked to the CO_2-eq concentration† stabilization target pCO_2eq_{stab} [ppm by volume (ppmv)] through the simple relation

$$dT_{stab} = dT_{2xCO_2} \cdot \frac{dQ_{stab}}{dQ_{2xCO_2}}, \quad [1]$$

in which dT_{2xCO_2} (°C) is the equilibrium temperature change associated with the radiative forcing dQ_{2xCO_2} (Wm^{-2}) at a doubling of CO_2 concentration and we calculate the radiative forcing dQ_{stab} (Wm^{-2}) implied by pCO_2eq_{stab} from (ref. 21):

$$dQ_{stab} = 5.34 ln(pCO_2eq_{stab}/278). \quad [2]$$

For estimating the global surface-air temperature change that will result from a specific level at which greenhouse gas (GHG) concentrations are stabilized, one needs to know the value of the climate sensitivity dT_{2xCO_2}. Here, we will reverse this problem. If for a chosen concentration target the temperature needs to remain below a certain temperature target, the climate sensi-

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†The CO_2-eq concentration is defined here as the equivalent CO_2 concentration that would result in equal radiative forcing as the total of the mix of different anthropogenic forcings in the model. In IMAGE 2.3 the concentrations are projected for all Kyoto and Montreal gases, tropospheric and stratospheric ozone, and sulphate, organic carbon and black carbon aerosols from anthropogenic sources.

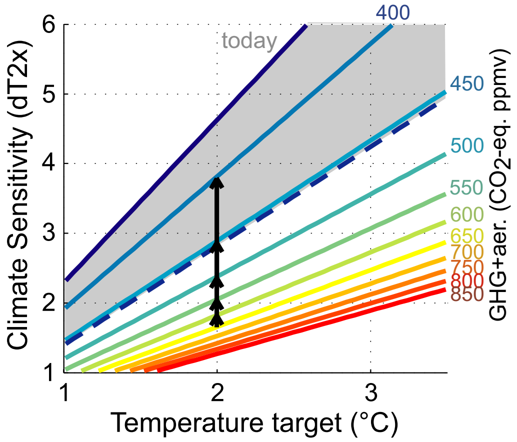

Fig. 1. The allowed, or maximum climate sensitivity that permits the achievement of climate targets (global-mean surface-air temperature change relative to preindustrial) at a range of GHG concentration levels (isolines). The black arrows illustrate more rapid increase in allowed climate sensitivity with decreasing concentrations at lower concentration levels. For comparison, we also show the hypothetical cases if concentrations were fixed at today's radiative forcing levels, including (≈1.6 W/m^2; full-line boundary of shaded area) and if only long-lived GHGs were considered by e.g., excluding aerosol-related cooling (≈2.6 W/m^2; dashed boundary).

tivity must be lower than a certain "allowed" value. Thus, we define an allowed value of the climate sensitivity dT_{2xCO_2} (°C) by

$$dT^*_{2xCO_2} = dT_{stab} \cdot \frac{dQ_{2xCO_2}}{dQ_{stab}}. \quad [3]$$

Results

Combining Temperature and Concentration Targets: Allowed Climate Sensitivity. Fig. 1 shows values for the allowed climate sensitivity for a range of temperature and concentration targets. For instance, if CO_2-equivalent concentrations are allowed to stabilize at a value of 650 ppmv, the European Union's 2 °C temperature target (22) can be achieved only if the climate sensitivity is lower than ≈1.6 °C. For comparison, the IPCC estimates that the climate sensitivity is very unlikely to be <1.5 °C (23) (see Fig. 2 and further discussion in *Methods*).

If the concentration target is lowered to 550 ppmv the allowed climate sensitivity (to meet the temperature target of 2 °C) rises

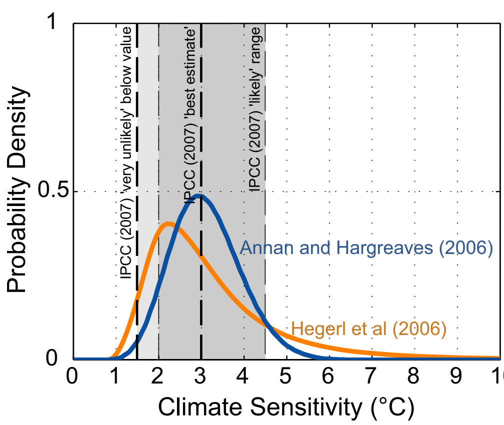

Fig. 2. PDF of equilibrium climate sensitivity of Annan and Hargreaves (24) used in this assessment. The shaded area indicates the range of the IPCC estimates (23), with a best estimate value of 3 °C. For comparison the differing PDF estimate by Hegerl *et al.* (28), used for the sensitivity analysis in this article, is shown as well.

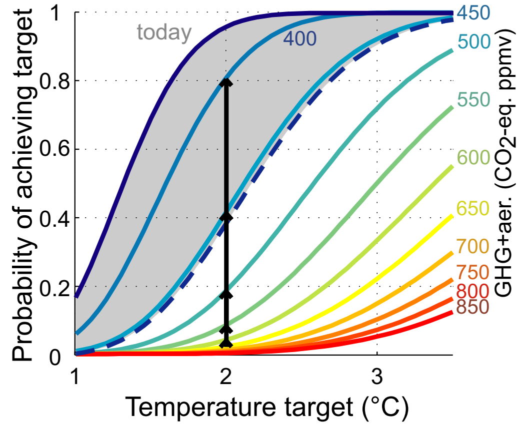

Fig. 3. The probability of achieving climate targets (global-mean surface–air temperature change relative to preindustrial) at a range of GHG concentration levels (isolines). To calculate probabilities, the probability distribution function of climate sensitivity was used as estimated by Annan and Hargreaves (24). The black arrows illustrate the more rapid increase in probability of reaching a climate target with decreasing concentrations at lower concentration levels. For comparison, we also show the hypothetical cases if concentrations were fixed at today's radiative forcing levels including (≈1.6 W/m^2; full-line boundary of shaded area) and if only long-lived GHGs were considered by e.g., excluding aerosol-related cooling (≈2.6 W/m^2; dashed boundary).

by 0.4 °C to a value of 2.0 °C. It rises more rapidly by a further 0.9 °C to a value of 2.9 °C if the concentration target is lowered by a further 100 ppmv to 450 ppmv. This finding shows that the allowed climate sensitivity compatible with a given climate target rises nonlinearly as CO_2-eq levels drop. The increased spacing between concentration isolines in Fig. 1 at lower concentrations is caused by the inverse relationship between allowed sensitivity and concentration (Eq. **3**) and the logarithmic relationship between CO_2 concentration and radiative forcing ("saturation"; Eq. **2**). At lower concentration levels, the combination of these effects allows for a quicker rise of allowed climate sensitivity with decreasing concentration. The strength of these effects increases monotonously with lower concentrations and also when the temperature target is relaxed. For example, the allowed climate sensitivity rises by ≈1 °C at temperature target 1.5 °C if the concentration drops from 500 to 400 ppmv, as opposed to the rise of almost 1.5 °C at temperature target 2 °C.

The Probability of Achieving Temperature Targets. The probability that the temperature target is achieved for a specific concentration level is equal to the probability that the "real" dT_{2xCO_2} is lower than the allowed $dT^*_{2xCO_2}$. In the previous section, we estimated the allowed climate sensitivity to be 1.6 °C for climate target 2.0 °C at 650 ppmv. According to the probability density function (PDF) for the climate sensitivity of Annan and Hargreaves (24), used as default in this article (see Fig. 2 and *Methods*), the probability that the climate sensitivity is <1.6 °C is <5%. Thus, the probability that the 2 °C target can be achieved with CO_2-eq reaching 650 ppmv is <5% (see Fig. 3, combining information from Figs. 1 and 2). If we assume the climate sensitivity is equal to IPCC's best estimate of 3.0 °C (23), we see in Fig. 1 that concentrations should be limited to ≈450 ppmv. Fig. 3 shows that at 450 ppmv the probability to achieve the 2 °C target is ≈40%. However, the probability rises rapidly when decreasing long-term concentration further from 40% at 450 ppmv, 80% at 400 ppmv, and 95% at 375 ppmv.

The probability of reaching the target rises most rapidly with decreasing concentration when the allowed climate sensitivity is near the PDF peak (region of high probability density). This

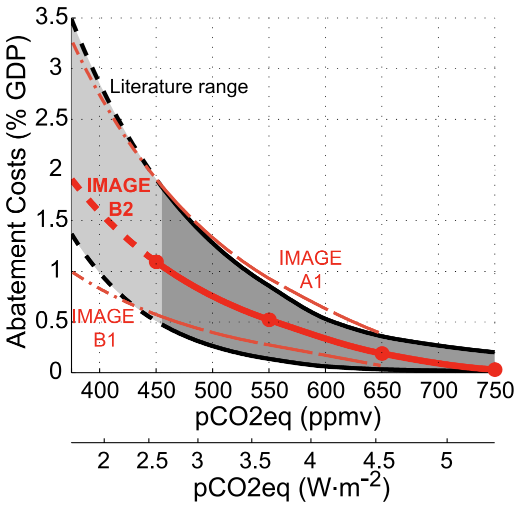

Fig. 4. The costs of decreasing stabilization levels of GHG concentrations. The costs have been extrapolated exponentially to the 375 ppmv CO_2-eq concentration level (dashed lines; see *Methods*). The additional *x* axis illustrates the conversion between CO_2-eq concentration levels and the corresponding radiative forcing.

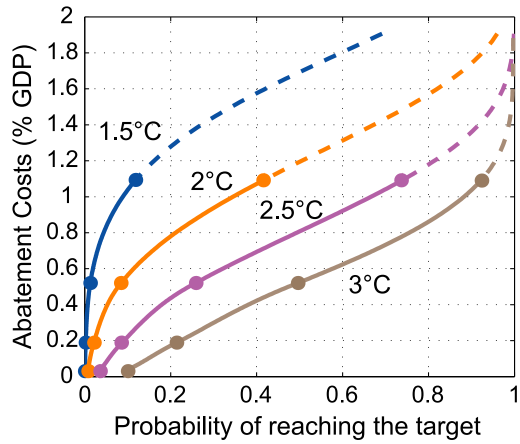

Fig. 5. The costs of increasing the probability of achieving global-mean temperature targets (relative to preindustrial) as projected by the IMAGE-2.3 model. See Fig. 4 legend for explanation of dashed lines.

additional nonlinearity transforms the concentration isolines first seen in Fig. 1 to curve up in Fig. 3 in the range of allowed climate sensitivities below the PDF peak and flatten out for climate sensitivities above the PDF peak. For our default PDF (Fig. 2), the transformation of concentration isolines is strongest at allowed climate sensitivities between 2.5 °C and 3.5 °C, roughly corresponding to concentration levels between 500 and 400 ppmv for the 2 °C climate target (Fig. 1). Combined with the first nonlinearities (stronger for lower concentrations), this transformation leads to the sharpest increase in the probability of achieving the 2 °C target between 450 ppmv (40%) and 400 ppmv (80%): an increase in probability of 40% for a relatively small concentration reduction of 50 ppmv. Thus, lowering long-term GHG concentrations effectively increases the probability of reaching a target temperature, whereas nonlinearities cause a particularly rapid increase in probability for a limited range of concentrations, defined by the location of the peak in climate sensitivity PDF, but skewed to the side of lower concentrations because of the other nonlinearities.

The Costs of Reducing Climate Change Risk. If one combines the probability estimates of Fig. 3 with cost estimates of stabilizing GHG concentrations at specific levels, one is able to explore the additional abatement costs required to increase the probability of reaching a temperature target. In this study, we use the abatement costs as estimated by the IMAGE-2.3 model (see Fig. 4, *Methods*, and ref. 25), which includes the TIMER global energy model. This estimate covers the direct (annual) costs of climate policy, but does not take into account the costs related to a change in fuel trade or macroeconomic impacts (including sectoral changes or trade impacts). We have expressed these costs in terms of the net present value (NPV) of abatement costs over the 2005–2100 period divided by NPV of gross domestic product (GDP) (the cumulative, discounted GDP). For the abatement costs, a discount rate of 5% has been used (actual discount rate applied, not pure rate of time preference). The value is consistent with the discount rate applied by the IPCC in presenting the NPV of abatement costs in both its third and fourth assessment reports (40).

Starting our cost analysis of increasing probabilities with the abatement costs calculated by the IMAGE-2.3 model shows that to increase the probability of meeting a 2 °C target from <5% to 10%, the abatement costs will need to be increased from ≈0.2 to >0.5% of GDP (Fig. 5). To reach a probability of 40%, the costs rise to 1.1% of GDP. To realize a desired probability approaching 90%, the costs will rise further and go beyond the range of the IMAGE-2.3 calculations. Although the number of studies at stabilization target at such low levels is severely limited, some indicative scenarios show that technically these levels can be reached, for instance by using combinations of bio-energy and carbon capture and storage (26, 27). Based on an exponential extrapolation of cost estimates to low concentration levels (see *Methods*), the abatement costs would be on the order of 2% of GDP when a 90% probability is to be reached. As is to be expected, increasing the probability of reaching a particular target leads to higher costs levels, but also choosing a more ambitious target (e.g., 1.5 °C) leads to higher costs.

Fig. 5 exemplifies the tradeoff between raising the probability of meeting a certain climate target and the increase in climate-mitigation costs. A crucial and very prominent feature of Fig. 5 is that for a large range of probability levels, probabilities rise roughly proportional to the increases in costs as provided by IMAGE-2.3 calculations. Within the near-linear segment (constant returns to scale), the quick rise in costs is counterbalanced by an equally fast increase in probabilities when concentrations are lowered, the latter caused by the nonlinear effects discussed above. Thus, shifting the attention away from concentration targets to the probability of achieving temperature targets (more relevant for limiting climate-change impacts) puts the familiar exponential cost rise as displayed in Fig. 4 in a different light.

Apart from near-linearity, several more observations are noteworthy regarding the shape of the curves in Fig. 5. First, the curves for different temperature targets are roughly parallel over the major part of the probability domain. Shifting to a lower temperature target will cost the same for any fixed probability to reach the target. Second, although the curves are near-linear for the most part, when the probability of meeting a climate target is already high (e.g., >90%), only small additional gains in probability are achieved for further cost increases. Finally, different temperature targets show quite different behavior at low probabilities. For strict temperature targets, an investment threshold needs to be crossed in the sense that low costs hardly increase the probability to achieve the target. Most strikingly in Fig. 5 for the 1.5 °C target, costs increase sharply to merely reach the lower edge of the linear "plateau." This "investment threshold" has ultimately disappeared for the 3 °C target, making the relationship between costs and probability near-linear over the full domain, very high probabilities excepted.

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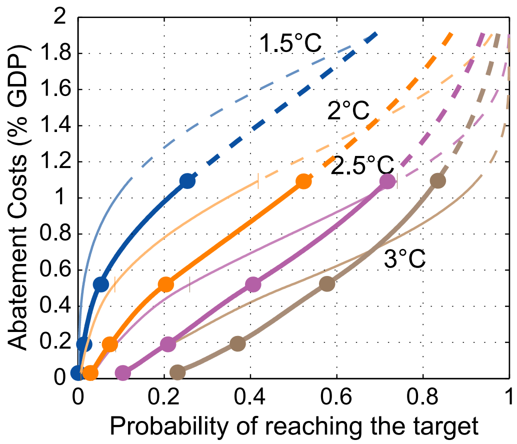

Fig. 6. The costs of increasing the probability of achieving global-mean temperature targets (relative to preindustrial) as projected by the IMAGE-2.3 model using the alternative PDF for climate sensitivity of Hegerl *et al.* (28). For reference, the thin lines indicate the results using the default PDF for climate sensitivity as in Fig. 5. See Fig. 4 legend for explanation of dashed lines.

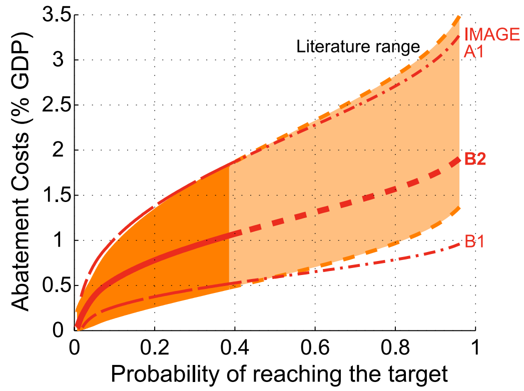

Fig. 7. The costs of increasing the probability of achieving global-mean temperature targets (relative to preindustrial). The shaded area indicates 10% and 90% boundaries of costs estimated by a large sample of model experiments from literature (see *Methods*). The red lines indicate the IMAGE-2.3 cost estimates for the A1, B1, and B2 (as in Fig. 4) baselines. See Fig. 4 legend for explanation of dashed lines.

The Robustness of Constant Returns to Scale. Although we have discussed the underlying causes of the linear segment in the curve, the exact shape of the curve remains an empirical result. A crucial question is when the costs/probability curves depart from near-linearity and under what circumstances. We hypothesize it is possible that near-linearity holds for a PDF of climate sensitivity that is relatively constrained and a cost estimate that shows a medium rate of increase for lower concentration levels. If the PDF is relatively constrained, the near-linearity in the relation roughly holds for the central probability levels of 25–75%, which is the area of probabilities around the peak in the PDF. Thus, probabilities rise quickly here and a near-linear section results, if the costs do not rise much faster.

To test the robustness of our empirical result to changes in the estimate of climate sensitivity, we show in Fig. 6 the results for the alternative PDF estimate of Hegerl *et al.* (28). Using this PDF illustrates the effect of a lower medium value, and the effect of a longer tail, i.e., a small, but finite probability of very large climate sensitivities (see Fig. 2). The lower median value means that a faster increase of probabilities can be achieved at relatively modest initial costs. However, the longer tail causes the linear relation to break down quicker and high probabilities are more difficult to achieve. Nonetheless, for each temperature target, a long near-linear segment can still be distinguished as before.

A further test of linearity is illustrated in Fig. 7, extending the cost estimates to the full literature range as explained in *Methods* (see Fig. 4). Only the 2 °C target is shown in Fig. 7, to avoid confusion caused by intersecting curves. We see that both the 10% and 90% boundaries of the cost range from the literature behave roughly like the IMAGE-2.3 estimates. Thus, for a large set of conditions, there is a constant return to scale: increased mitigation expenditure proportionally increases the probability of meeting a target. Interestingly, the investment threshold for low probabilities seems to be smaller for the 10% lower boundary. For the literature range in Fig. 7 the segment of the curves above probabilities of 40% is covered by the extrapolated cost estimates. However, the constant return to scale characteristic is not a spurious result from the extrapolated cost curves. For example, Figs. 5 and 6 show that for the IMAGE cost estimates the full near-linear segment is covered by the real cost estimates for the 2.5 °C and 3 °C targets.

A major influence on cost estimates of stabilization is the baseline scenario. For a higher baseline scenario, cheaper mitigation options are exhausted more rapidly, leaving relatively more expensive options for the lower stabilization levels. The result is a steeper rise in costs with lowering stabilization levels for higher baselines, potentially reducing the length of the linear segment in the probability curve. Obviously, a merely steeper (first derivative) cost curve will not affect linearity, but the cost curve bending up more sharply (second derivative) will.

To explore the impact of baselines on the curve shapes, we show in Fig. 4 the cost estimates of stabilization for different baseline scenarios in IMAGE. Where the abatement costs in B2 are close to the literature median, costs of stabilization from the A1 baseline largely overlap the upper literature-range boundary, whereas B1 results in an even milder increase of costs with lowering concentration than the lower boundary of the literature range. However, Fig. 7 shows that the changes in near-linearity of the probability curves are virtually negligible. Only for the B1 baseline the near-linear segment seems to start at somewhat lower probabilities, reproducing the behavior of the 10% lower boundary of the literature range. Thus, the baseline may affect the investment threshold. However, the dominant effect of the baseline seems to be on the slope of the near-linear segment (increasing for a higher baseline), not on the length of this segment.

Another potential impact on the curve shape can be expected from the discount rate applied. Higher discount rates increase the relative importance of near-term costs. Because low stabilization targets require earlier action and thus have higher costs in the near term, higher discount rates make low stabilization levels relatively more expensive and the abatement-cost curves steeper. Different views on what discount rate needs to be used in accounting for long-term costs (and benefits) of climate policy have been brought forward by Nordhaus (2), Stern (1), Weitzman (29), and others. The choice of discount rate includes a value judgment about the importance attached to (risks for) the welfare of future generations. On the low side, Stern proposes a discounting rate of 1.4% (based on a 0.1% pure time preference); whereas,on the high side Nordhaus uses discount rates >5%. The United Kingdom Treasury (30) recommends in its Green Book using a decreasing discount rate ≈3.5–2.5% for long-term appraisals. The flat 5% discount rate applied here (consistent with the numbers in the IPCC's fourth assessment report) can be regarded as a relatively high value compared with the range of values proposed in literature. As argued above, a lower value would lead to more linearity (in other words, in most cases results will be more linear than shown here). We have explored the impact of abatement costs by using a Stern-based

1.4% discount rate as postcalculation without changing the timing of the scenarios (data not shown). Here, the impact on linearity is small, as a result of simultaneous changes in both abatement costs and GDP. This simultaneity underestimates the real impact of the use of lower discount rates (which would lead to more linear curves).

Our main finding of a near-linear relationship between mitigation costs and the probability to achieve a fixed temperature-change target is robust for the sensitivity tests above. However, the exercise in this article uses a very simple model framework to explore this relationship. The advantage is the high level of transparency and ease of verification. The simple equations are adequate to introduce this issue and show the near-linear relationship to first order. A major disadvantage is that the numerical results cannot be applied directly in a climate-policy context. For the latter, the calculations should be performed with a climate-modeling framework that is thoroughly validated against observations and captures the time-dependant chain from emissions to temperature change more adequately. This is especially true for examining the effect of using peaking or overshoot profiles (31), instead of long-term stabilization. We intend to use the more complex modeling frameworks we have applied before (17, 25) to further explore the relationship between costs and probabilities, now that we have established the first-order relationship to be near-linear.

Our analysis shows that the near-linear segment in the probability graphs is found for concentrations <550 ppmv CO_2-eq. Within this near-linear segment, mitigation efforts directly pay off. This is a compelling argument for intensifying the research efforts into technological and economical options to extend the cost estimates of mitigation efforts to lower concentration levels. Such research would greatly help to solve the problem that, for targets of 2 °C and below, the major part of our probability curve is derived from the extrapolated cost estimates.

Two basic problems that cannot be avoided for now, or the near future, are the large uncertainty in estimated costs and the variety of estimates for the PDF of climate sensitivity. Although the constant returns to scale relation that we found seems to be robust with a wide range of cost estimates and different climate-sensitivity PDFs, the policymaker is still left with considerable uncertainty regarding the actual level of costs required to achieve a certain probability of achieving a climate target. However, these problems are not a unique characteristic of this probabilistic framework, but will continue to plague the broader climate debate in the foreseeable future.

Discussion

The uncertainty in climate sensitivity is a central obstacle in developing climate policy. It remains to be seen if the uncertainty range of climate sensitivity might be narrowed by the 2020s as our knowledge of the climate system improves (32), or that climate sensitivity will remain difficult to constrain on the high side, because of fundamental characteristics of the climate system (33). In the first case, a clearer picture would slowly emerge of the expected returns on costs to reduce climate-change risk. We have tested, but not shown in this article, the impact of strongly narrowing the climate-sensitivity PDF. If the best estimate remains the same, narrowing the PDF increases the investment threshold at the low probability side for all temperature targets, but lowers the costs to achieve high probability, leaving near-linearity intact for medium probabilities. Thus, if climate policy is targeted at higher probabilities, further constraining climate sensitivity will not adversely impact the investment decision. Obviously, the situation is different if the best estimate shifts significantly because of progressing scientific understanding.

In the second case of a lasting significant probability of high values for climate sensitivity, costs will remain to rise sharply to reach a higher probability to achieve climate targets. However, mitigation efforts would then perhaps be even more crucial for limiting the higher climate-change risk associated with such high climate sensitivities. The increased inertia of the climate system for high climate sensitivities (34) also makes reductions in emissions and concentrations more effective.

We have shown that over a large range of probabilities to reach a temperature target the marginal gains (of increasing certainty to reach climate targets) of each additional dollar spent on climate policy are constant, despite the fact that costs increase exponentially for stabilization concentration levels. In other words, there is a constant return for increasing mitigation costs. All of this leads to a compelling argument for seeking more certainty in limiting climate-change damages by lowering GHG concentrations, especially because monetary or nonmonetary damages appear to rise rapidly with temperature (35). The probability of limiting warming to specific levels appears to rise near-linearly with the expenditure on emission reductions. When taken together with the recent findings of the IPCC AR4 (41) that lowering global-mean temperature increase reduces risks, this result indicates that expenditure on emission reductions can directly pay off with reduced risks and impacts in many human and natural systems.

Methods

PDF of Climate Sensitivity. Attempts to constrain the uncertainty in dT_{2XCO2} and estimate its PDF (23) include analyses of General Circulation Model characteristics (36) and subjective expert judgments (37), consistency analyses using paleoclimatic data (38), or recent climate observations (39). The PDF estimates applied in this article, draw from multiple lines of evidence and methods. In this study, we applied the PDF estimate by Annan and Hargreaves (24) as default (Fig. 2). The median of this PDF is close to the IPCC's most likely value for climate sensitivity of 3 °C (23). The 10% boundary at 2.1 °C and the 90% level at 4.2 °C are close to the boundaries of the likely IPCC range of 2 °C to 4.5 °C. This finding means that this PDF is more constrained than the IPCC range, because the IPCC assesses the lower 10% boundary to be at 1.5 °C (very unlikely below) and does not provide a very likely (90%) upper bound at all (23), rather finding that ''values substantially >4.5 °C cannot be excluded.''

According to the estimate of Annan and Hargreaves (24), the probability that dT_{2XCO2} is >4.5 °C is <5%. By contrast, the alternative PDF estimate of Hegerl *et al.* (28) has lower values for the median (2.8 °C) and a 10% boundary (1.7 °C) close to that of the IPCC, but a much longer tail than estimated by Annan and Hargreaves (24), meaning that the climate sensitivity is less constrained on the high side (90% at 5.1 °C and >5% probability of dT_{2XCO_2} >6 °C).

The Costs of Stabilizing GHGs. For stabilizing GHG concentrations (at dQ_{stab}), emissions need to be reduced from baseline development. A large number of recent scenario studies have estimated the costs of stabilizing GHGs at different levels. The costs estimates differ widely among different studies, depending on baseline emissions, technology assumptions, and the way climate policy is implemented (see ref. 18). In addition, different cost metrics are used in the literature to describe the costs of climate policy, in particular (*i*) additional direct expenditures on abatement (here called abatement costs, used by both partial and full equilibrium models) and (*ii*) welfare or consumption losses (used by full equilibrium models). Although the latter represents a more comprehensive cost metric, the results also are more uncertain (8).

The IMAGE-2.3 mitigation scenarios describe how emissions can be stabilized at 750, 650, 550, and 450 ppmv CO_2-eq starting from the updated IMAGE implementation of the IPCC-SRES B2 scenario (42). The scenario is based on medium assumptions for population growth, economic growth, and more general trends such as globalization and technology development. The IMAGE/TIMER model includes a very wide range of mitigation options, including changes in the energy sector (mostly to reduce CO_2 emissions), reforestation, and reduction of non-CO_2 gas emissions. A special case is the 450 stabilization scenario. This long-term stabilization level is achieved with a temporary overshoot in the second half of the 21st century, reaching a level of 480 ppmv CO_2-eq at the end of the century.

For comparison, we also include the abatement cost estimates of a wide range of other models as summarized by the IPCC (18). Because for most of these studies abatement costs are not directly available, we follow the same method as presented in the IPCC report using as proxy the product of marginal

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abatement costs and the GHG reductions from baseline divided by a constant. Using a value of 2.5 for this constant leads to a conservative (high) estimate of actual abatement costs in the different models. As shown in Fig. 4, the range of different model outcomes, defined by the 10% and 90% intervals at each concentration level, leads to estimates that are considerably higher and considerably lower than the IMAGE 2.3 estimates (with baseline emissions as dominant factor in explaining this range).

Very little scenarios have been published that aim for stabilization <450 ppmv CO_2-eq. Still some exploratory studies suggest that low stabilization levels up to 400 ppmv CO_2-eq and even lower are technically achievable at exponentially increasing costs, based on identifiable technologies such as bio-energy and carbon capture and storage (26, 27). Here, we use these studies as a basis for linear regression of the logarithm of the abatement costs on the concentration levels to extrapolate to the lowest level. The sole motivation for this is to explore the relationship between costs and probability at lower concentrations, higher probability, and higher cost levels than available from existing scenarios. We have extrapolated down to a level of 375 ppmv, a case in which CO_2-eq concentration is imagined to return to present-day values (including negative anthropogenic forcings) in the long term. This is certainly not intended as an estimate of costs for mitigation efforts that will ''freeze'' present-day forcing without delay, the costs of which would be astronomical. We stress that the exponential extrapolation to low concentration levels is hypothetical and only intended to extend the exploration of the relationship between probabilities and costs to low concentrations.

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