Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs

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How can dangerous interference with the climate system be avoided? Science can help decision-makers answer this political question. Earlier publications have focused on the probability of keeping global mean temperature change below certain thresholds by stabilizing greenhouse gas concentrations at particular levels. We compare the results of such "stabilization profiles" with a set of "peaking profiles" that reduce emissions further after stabilization and thus result in a concentration peak. Given the inertia in the climate system, stabilization profiles lead to ongoing warming beyond 2100 until the temperature reaches equilibrium. This warming partly can be prevented for peaking profiles. In this way, these profiles can increase the likelihood of achieving temperature thresholds by 10–20% compared with the likelihood for the associated stabilization profiles. Because the additional mitigation efforts and thus costs for peaking profiles lie mainly beyond 2100, peaking profiles achieving temperature thresholds with the same likelihood as the original stabilization profile, but at considerably lower cost (up to 40%), can be identified. The magnitude of the cost reductions depends on the assumptions on discounting. Peaking profiles and overshoot profiles with a limited overshoot may, in particular, play an important role in making more ambitious climate targets feasible.

abatement costs | concentration stabilization | climate change | integrated assessment model | multigas emission pathway

The interpretation of "dangerous" or "tolerable" climate change, and how this relates to targets for global mean temperature increase, is clearly not only a scientific question but also a normative decision. The answer is highly dependent on the interpretation of uncertainties in the cause–effect chain of climate change and on political choices about the assumed acceptable level of risk. Some of the recent scientific research suggests that climate risks could be substantial for an increase of 1–3°C compared with preindustrial levels (1–7). These risks include the loss of unique ecosystems, as found in coral reefs, the Arctic, and alpine regions, or an irreversible melting of the Greenland ice sheet. In an attempt to avoid such risks, the European Union has adopted a climate target of limiting global average temperature increase to a maximum of 2°C above the preindustrial level (8). The probability of meeting temperature targets is very sensitive to the uncertainty associated with the climate sensitivity (defined as the equilibrium global mean surface temperature increase caused by a doubling of atmospheric CO_2) (9). Studies have published probability density functions (PDFs) of the climate sensitivity (see, for example, refs. 10 and 11). According to several studies, these PDFs can be used for a risk analysis of climate change (9, 12–16).

Along with climate sensitivity, the concentration trajectory also plays a role in the probability of transient temperature staying below a certain temperature target. So far, the literature focuses mainly on stabilization of greenhouse gas (GHG) concentration, as mentioned in the United Nations Framework Convention on Climate Change (UNFCCC) objective. However, other GHG concentration pathways also may be considered. First, CO_2-equivalent concentration might be allowed to peak and decline afterward (peaking profiles) to avoid a further increase in climate change that would result from a continued stabilization of concentrations (15, 17). Alternatively, concentrations also may be allowed to temporarily overshoot the stabilization target. The next section discusses the characteristics of different concentration profiles.

Here we present our analysis of abatement costs and climate benefits (in terms of transient likelihood of meeting temperature targets) of stabilization, as well as peaking and overshoot profiles to show how these compare with the climate benefits and costs. We used the FAIR-SiMCaP model (14, 17) for the analysis and calculated the global abatement costs and probabilistic temperature implications for a wide range of multigas emissions pathways (emissions of all GHGs, aerosols, and all other significant radiatively active gases).

Concentration Profiles: Peaking Versus Stabilization

The different types of concentration profiles studied in the literature are illustrated in Fig. 1. First of all, "stabilization" profiles are by far the most commonly studied profiles for CO_2 concentrations (see, for example, refs. 18 and 19–21) and, more recently, CO_2-equivalent concentrations (14, 15, 17, 22, 23).

Secondly, "overshoot stabilization" profiles that temporarily overshoot, but ultimately lead to, stabilization have been analyzed in several studies in the past (e.g., refs. 18 and 21). More recently, Wigley (24), for instance, has analyzed a profile that initially led to an overshoot (600 ppm CO_2) but finally reached a stabilization level of 550 ppm CO_2. Wigley suggested that overshoot profiles are cost-effective strategies for meeting temperature targets (although this was not supported by cost analyses). O'Neill and Oppenheimer (23) analyzed overshoot profiles that even exceed the ultimate stabilization levels of 500–700 ppm CO_2-equivalent concentration by 100 ppm, and they showed that the associated incremental warming may substantially increase the risks of exceeding critical climate thresholds beyond which ecosystems are known to be unable to adapt. Schneider and Mastandrea (25) also demonstrated in their probabilistic framework that these overshoot profiles can significantly increase the likelihood of exceeding "dangerous" climate impact thresholds. Collectively, these studies show some of the strengths and weaknesses of overshoot strategies, which critically depend on the degree of overshoot: a large and lengthy overshoot influences transient temperature increase in contrast to a limited, temporary overshoot (given the inertia in the climate system). It should be noted that as a result of socioeconomic inertia in reducing emissions, low concentration stabilization targets (such as 450 and 400 ppm CO_2-equivalent concentrations or 350 ppm CO_2) may be unfeasible unless overshoot is allowed (14, 15, 17, 26).

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Abbreviations: PDF, probability density functions; GHG, greenhouse gas; MAC, marginal abatement costs; GWP, global warming potentials; GDP, gross domestic product; NPV, net present value; IPCC, Intergovernmental Panel on Climate Change.

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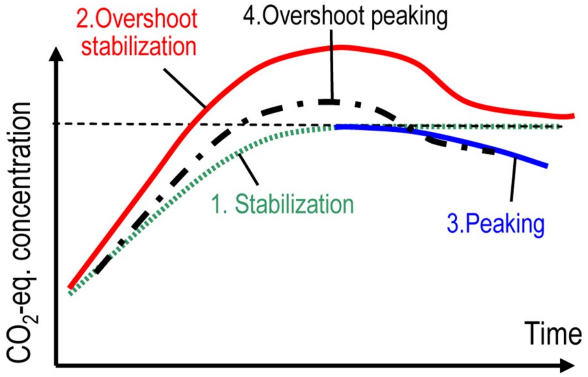

Fig. 1. Schematic illustration of stabilization, overshoot, and peaking profiles.

"Peaking" profiles, a third type (see also ref. 15), more or less follow the trajectory of stabilization profiles but continue the pace of emission reduction after stabilization. By reducing concentrations after stabilization, it is possible to prevent some of the temperature increase ("committed warming") that would still occur after this concentration peak (Fig. 1). In this way, peaking significantly increases the likelihood of meeting long-term temperature targets (see also ref. 17). Obviously, overshoot and peaking can be combined to create profiles that imply a temporary limited "overshoot" of the concentration level, followed by further reductions. Such "overshoot peaking" profiles (type 4) are analyzed here. Such profiles, if well designed, have the ability to decrease costs (attributable to higher short-term emissions), whereas the likelihood of meeting temperature targets is increased by ongoing reductions beyond the concentration peak. However, there is a price to pay too. Overshoot profiles will have a slightly higher rate of temperature increase and will make it more difficult to reach low concentration levels if adjusting existing targets downward is deemed to be required (e.g., if climate change results to be more severe than expected). It should be noted that the terms peaking and overshoot are relative to a particular stabilization profile. For example, the same peaking profile compared with stabilization at 550 ppm CO_2-equivalent concentration can be called an overshoot peaking profile compared with stabilization at 450 ppm CO_2-equivalent concentration.

Frame *et al.* (27) recently also focused on alternatives to stabilization scenarios and concluded that, given the uncertainties in the climate sensitivity, it is more appropriate to focus on peak scenarios. Not only does this prevent further warming, but it also reduces uncertainty. Uncertainty about (short-term) transient climate response is less than uncertainty about equilibrium climate sensitivity.

Methodology

We have gone beyond existing work by focusing on the tradeoff between costs and probabilities of reaching temperature targets for stabilization and peaking profiles. We used the FAIR-SiMCaP model (14, 17), combining a simple abatement costs model and a module to explore different pathways that meet climate targets. The simple cost model distributes the difference between baseline and the global emissions pathway over the different GHGs and emission sources by using regional marginal abatement costs (MAC) curves (28). The SiMCaP pathfinder module makes use of an iterative procedure to find multigas emissions pathways that correspond to a concentration target. The emissions include all major GHGs (CO_2, CH_4, N_2O, hydrofluorocarbons, perfluorocarbons, and SF_6, i.e., the so-called Kyoto GHGs and the chlorofluorocarbons), ozone precursors (volatile organic compounds, CO, and NO_x), and sulfur aerosols (SO_2).The global climate calculations make use of the simple climate model MAGICC 4.1 (10, 29). In the analysis, the timing of emission reduction was determined by performing a large number of different runs in combination with exogenously set rules [see further and supporting information (SI) *Text*]. For each time step, a cost-effective split is determined in reductions of different GHGs using global warming potentials (GWPs).[†]

Abatement Costs. The model minimizes abatement costs in each point of time by using MAC curves. This costs metric captures the direct 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). In addition to the annual abatement costs [as percentage of gross domestic product (GDP)] used in this study, we also determined the net present value (NPV) of abatement costs over the 2005–2100 period. This value represents the cumulated costs over that period, but discounted over time, divided by NPV of GDP (the cumulative, discounted GDP). The review in ref. 32 suggests that our NPV of cost projections compare well to those of other studies, i.e., Azar *et al.* (26), Rao and Riahi (33), and Energy Modeling Forum (EMF) studies as reported in Intergovernmental Panel on Climate Change (IPCC) (20). In the literature, alternative cost metrics are used to describe the costs of climate policy, including abatement costs (used by both partial and full equilibrium models) and welfare losses (used by full equilibrium models). Although the latter may represent a more comprehensive cost metric, the results also are more uncertain (20, 31).

The MAC curves used in the calculations for energy- and industry-related CO_2 emissions were determined with the energy model TIMER 2.0 (32) by imposing a carbon tax and recording the induced reduction of CO_2 emissions. The MAC curves for carbon plantations were derived by using the IMAGE model (34). MAC curves from the EMF-21 project (35) were used for non-CO_2 GHG emissions. These curves have been made consistent with the baselines used here and made time-dependent to account for technology change and removal of implementation barriers over time (36) (see *SI Text*).

The NPV of cost calculations depend on the assumed discount rates. The discount rate applied here (main text) is 5%, which is consistent with the presentation of the NPV of abatement costs for stabilization scenarios in both the Third and Fourth IPCC Assessment Report. With this discount rate, costs in 100 years time become almost negligible (assuming constant costs after 2100, the contribution of the total 22nd century is likely to be $\approx$1% of that for the 21st century). In SI Figs. 6 and 7, however, we explore the results of alternative discount rates. Under the default discount rate in the main text, we do not have to include costs beyond 2100; clearly, presenting such long-term costs is speculative given the increasing lack of empirical foundation for cost estimates over such long time periods. However, as our scenarios (stabilization versus peaking) include very crucial differences in emissions after 2100, the use of alternative discount rates in the SI Text does include some indicative calculations on the potential impacts of extending cost calculation beyond 2100.

Baseline. The baseline scenario used here is the updated IMAGE/TIMER implementation of the IPCC-SRES B2 scenario (32) (hereafter known as the "B2 scenario"). The scenario is based on medium assumptions for population growth, economic growth, and more general trends such as globalization and technology development. In terms of quantification, the updated scenario roughly follows the reference scenario of the World

[†]Some authors have focused on alternative allocation rules across different gases by applying cost-optimization over time. It should be noted, however, that all existing climate policies use GWPs for this purpose and the difference in costs between cost-optimization and GWP-based approaches have proven to be small (30).

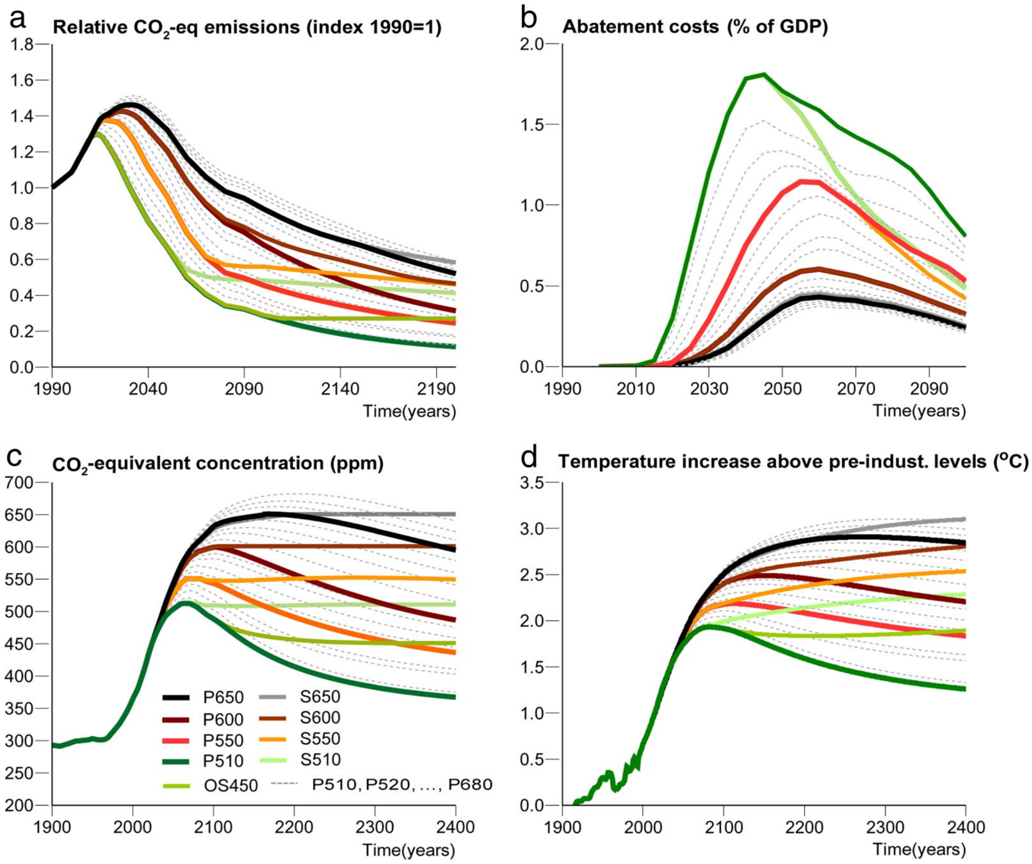

Fig. 2. The (GWP-weighted) emissions compared with 1990 levels (*a*); abatement costs (*b*); CO_2-equivalent concentration (*c*); the global average temperature increase compared with preindustrial levels (assuming a climate sensitivity of 2.5°C) (*d*) of the emissions pathways of the peaking and stabilization concentration profiles for 510, 550, 600, and 650 ppm (colored lines) and overshoot profiles—P510, P520, . . . , P680 with 10-ppm intervals—(gray dashed lines); and the OS450 stabilization pathway.

Energy Outlook 2004 (37); after 2030, economic assumptions converge to the original B2 trajectory. In this scenario, total Kyoto GHG emissions increase from the current 10 GtCeq to 23 GtCeq in 2100 (where GtCeq means gigatons of carbon equivalent). This value corresponds to an average baseline in the existing literature (38), leading to a GHG concentration that reaches 850 ppm CO_2-equivalent concentration by 2100.

Multigas Pathways. Most studies of emissions pathways (such as refs. 15 and 23) provide hypothetical emissions pathways that meet certain concentration stabilization targets. The emissions pathways used here cover all Kyoto gases[‡] and include existing climate policies (the Kyoto Protocol targets and the GHG intensity target for the United States). These pathways are based on estimates of technically feasible reductions.[§] Four main criteria to develop pathways were used that determine the timing of the emissions pathways (17). First, for each moment in time, the required level of emission reductions (by GHG) needs to be met by a corresponding level of emission reduction potential. Second, a maximum reduction rate was assumed, reflecting the technical (and political) inertia that limits emission reductions, avoiding premature replacement of existing fossil-fuel-based capital stock. As reduction rates in existing scenarios hardly exceed 2.5% per year (17), we chose maximum rates ranging from 1.5% to 2.5%, depending on the final concentration stabilization target. Third, the reductions compared with the baseline were, as far as possible, spread out over time. Fourth, and finally, the reduction rates only were allowed to change slowly over time (i.e., the second derivative of emissions), using a constraint of 0.25% points per year. Higher reduction rates were not explored but may be possible by using more optimistic assumptions on land use, efficiency, and biofuels (e.g., the availability of bioenergy in combination with carbon capture and storage) (32).

Analysis

Concentrations. Using the methodology described above, we developed emissions pathways leading to long-term stabilization CO_2-equivalent concentrations at 510, 550, 600, and 650 ppm (stabilization profiles S510, S550, S600, and S650) (17). The S510 stabilization profile equals the lowest achievable stabilization level without overshoot on the basis of the rules set here. In all emissions pathways, the reduction rates slow down in the second half of the century as concentrations approach the target concentration. On the basis of these profiles, we developed a second set of emissions pathways that initially follow the emission trajectory of the stabilization profiles. But these continue to reduce emissions after concentrations have reached the targeted stabilization level at a rate

[‡]The emissions of the ozone precursors and SO_2 were calculated with the TIMER model by using the same emission coefficients as those assumed under the baseline and simply quantifying the impact of changes in the energy system on these emissions. The chlorofluorocarbon emissions (regulated by the Montreal Protocol) follow the baseline emissions.

[§]The number of studies analyzing multigas stabilization scenarios below 550-ppm CO_2-equivalent concentration currently available in the literature are limited (see IPCC Fourth Assessment Report). Examples are refs. 30, 32, and 33. The stabilization scenarios used here are described in more detail in ref. 32.

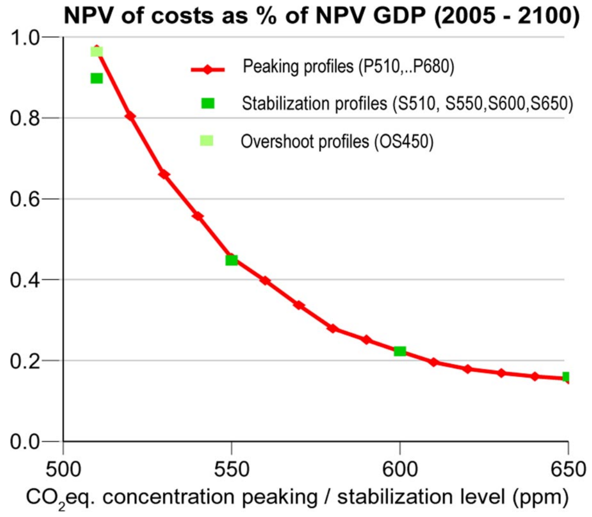

Fig. 3. NPV of abatement costs for different concentration peaking and stabilization levels (discount rate of 5%) as percentage of the NPV of GDP. The OS450 profile, with the same costs as P510, also is shown here for comparison.

of ≈40–50% below the reduction rate before stabilization.[¶] In other words, these profiles peak at concentrations of 510, 550, and 650 ppm (peaking profiles P510, P550, P600, and P650; see Fig. 2 *a* and *c*). These peak profiles were extended in a set from 510 ppm to 680 ppm, with intervals of 10 ppm through a combination of interpolation and subsequent model iterations (Fig. 2*c*) (see also *SI Text*). It should be noted that for peaking profiles, the likelihood of exceeding temperature targets depends on the peaking concentration level (see also ref. 16), as will be explained later. Finally, for comparison we also have included the overshoot stabilization pathway (OS450) of ref. 17, which is basically similar to the P510 pathway up to 2100, but after 2100 it differs because concentrations are stabilized at 450 ppm by 2200.

Emissions. We derived global GHG emissions (including land-use change and forestry CO_2 emissions) that decrease significantly in all scenarios (Fig. 2*a*). For the achievement of the lowest-concentration target (510 ppm), flexibility is very limited and global emissions need to reach a maximum in the next one to two decades. There is more flexibility for the other targets.

Abatement Costs. The costs as a percentage of GDP highly differ across the different stabilization and peaking targets (Fig. 2*b*).[‖] For the 510 and 550 ppm pathways (peaking and stabilization), costs as percentage of GDP reach a maximum level between 2020 and 2040 (1.2% of GDP for 550 ppm and 2% for 510 ppm). In most pathways, the relative cost (as percentage of GDP) actually declines in the second half of the century, as GDP growth outstrips the growth in abatement costs for most of the pathways. If the costs are discounted (NPV), the costs as a percentage of the NPV of GDP for the B2 baseline scenario vary between 0.2% of GDP for stabilization at 650 ppm and 1.2% of GDP in the 510-ppm case (with a discount rate of 5%; see Fig. 3).

Temperature Increase. The emissions pathways for the different concentration profiles lead to clearly different temperature increases, both during this century and in the long term. Fig. 2*d* shows the resulting (transient) temperature increase by using a single value for climate sensitivity (2.5°C). (The consequences of uncertainty in climate sensitivity will be discussed later.) There are a number of points to note here. First, as stated in the introduction, the transient temperature increase does not reach its equilibrium for many centuries after stabilization of GHG concentrations because of the large thermal inertia of the climate system, which, in turn, is largely determined by how rapidly heat is mixed down into the ocean. Second, the peaking profiles effectively prevent some of the temperature increase. As a result, peaking allows an increase in the likelihood of meeting the long-term temperature targets. Third, Fig. 2*d* shows that the peaking concentration at very low stabilization levels[**] is an important factor determining whether a 2°C temperature threshold will be achieved or not, and not the low stabilization level that is reached in the long term (see ref. 16) (shown by the peak in transient temperature).

Clearly, the temperature response of the different stabilization scenarios to a considerable depends extent on the climate sensitivity. Taking into account the uncertainty in the climate sensitivity [based on a log-normal distribution between 1.5 and 4.5°C (10)], we calculated the probabilistic temperature projections for the emissions pathways associated with the stabilization profiles (S510, S550, and S650), peaking profiles (P510, P550, and P650), and the transient global average temperature increase over time.[††] This finding allows us to compare the pathways and the associated likelihood of these profiles meeting long-term temperature targets, as shown in Fig. 4, which compares the results in 2100 (Fig. 4*a*) and 2200 (Fig. 4*b*). Fig. 4*c* indicates the likelihood of meeting the targets in the equilibrium situation for the various stabilization profiles. Again, under peaking, the overall likelihood of meeting a target depends on the peaking value, i.e., the maximum temperature increase reached at some time between 2000 and 2400 (see Fig. 4*c*). Obviously, more PDFs for climate sensitivity exist than the one used here, but using another PDF would not change the qualitative conclusions, only the magnitude.

Fig. 4 *a* and *b* shows that the likelihood of meeting temperature targets increases for the peaking profiles from 2100 to 2200, whereas the likelihood decreases for the stabilization profiles because of their ongoing temperature increase. Fig. 4 shows that according to our analysis the 550-ppm stabilization profile (equilibrium temperature increase) has a 26% chance of meeting the 2°C target, whereas for peaking at 550 ppm (maximum temperature increase), this increases to 34%. In other words, avoiding most of the additional warming after the peak can increase the probability of achieving a 2°C target by ≈8% compared with a stabilization profile.[‡‡] For peaking at 510 ppm, this probability to meet 2°C can be as high as 54% (compared with 39% under stabilization at 510 ppm). At higher concentration levels (e.g., 650 ppm), the question of peaking or stabilization becomes irrelevant for a 2°C target, as differences between the cases are very small. For higher temperature targets, however, the same argument also applies to higher concentration levels. For instance, peaking at 550 ppm increases the likelihood of achieving a 3°C target up to ≈95%, compared with only 62% for 550 ppm stabilization.

This discussion can be taken one step further. Fig. 5 combines the probability estimates for meeting the 2°C target (Fig. 4*c*) with the cost estimates shown in Fig. 3. The reason to focus on the results of

[¶]Less than 1% per year for a limited period (≈40–60 years).

[‖]As analyzed in ref. 32, these cost projections are beset with uncertainties, with the crucial uncertainties in baseline emissions, bioenergy use, and potential and technology development. Together, these uncertainties easily can double or halve the mitigation costs for a concentration target.

[**]These low concentration levels can be achieved only by overshoot profiles because emissions cannot be reduced fast enough to avoid an overshoot.

[††]For the probabilistic transient temperature calculations, the model takes into account the dependency among climate sensitivity, ocean diffusivity, and aerosol forcing, so as to match the historical temperature evolution; a method from ref. 16 is used.

[‡‡]If a different PDF for climate sensitivity is assumed, for example, the one by Andronova and Schlesinger (11), the likelihood of meeting thresholds would be much lower, and peaking as opposed to stabilization at 550 ppm would increase the probability of meeting 2°C from 7% to 11%.

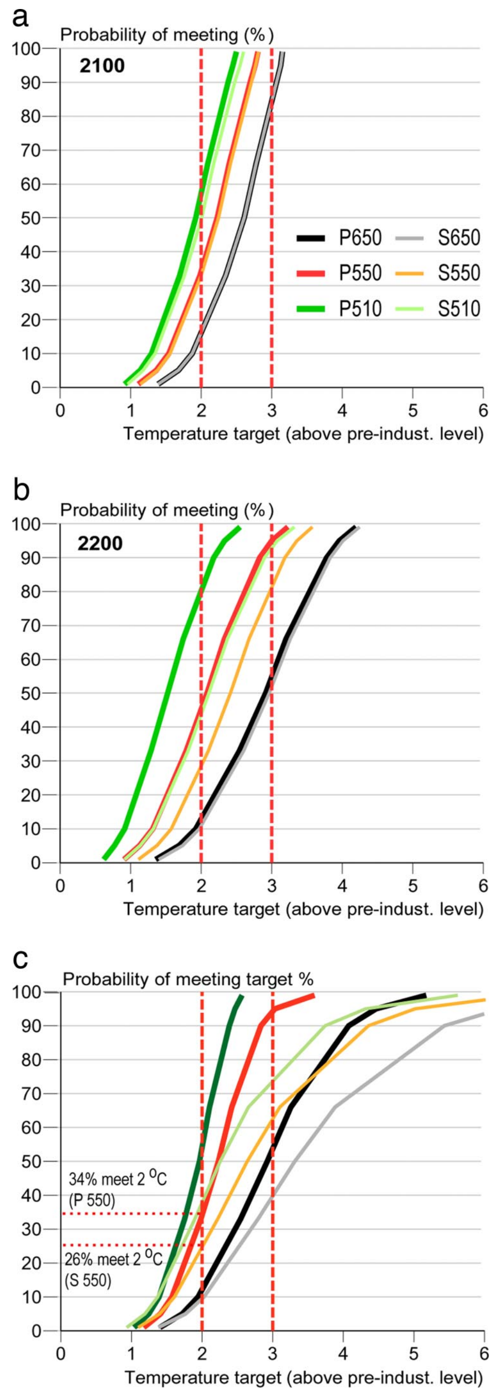

Fig. 4. Comparison of the probability of meeting of the indicated temperature thresholds for the emissions pathways of the peaking and stabilization concentration profiles for 510, 550, and 650 ppm (600 ppm is not shown here). The probabilistic temperature calculations are based on the climate sensitivity PDF by Wigley and Raper (10) (*a*–*c*). Probabilities of meeting target for transient temperature increase above preindustrial levels in 2100 (*a*) and 2200 (*b*), while probabilities of meeting target for equilibrium temperature increase for the stabilization profiles (*c*)—target for the maximum transient temperature increase that is reached sometime between 2000 and 2400 (see Fig. 2*d*) for the peaking profiles. Note that in *a*, the P650 and S650 lines overlap; this also holds for the P550 and S550 lines.

Fig. 4*c* and not on Fig. 4 *a* or *b* is that only the former captures the long-term consequences of stabilization and shows that to increase the probability to meet 2°C by using only stabilization profiles, costs for implementing climate policy necessarily increase as well (as

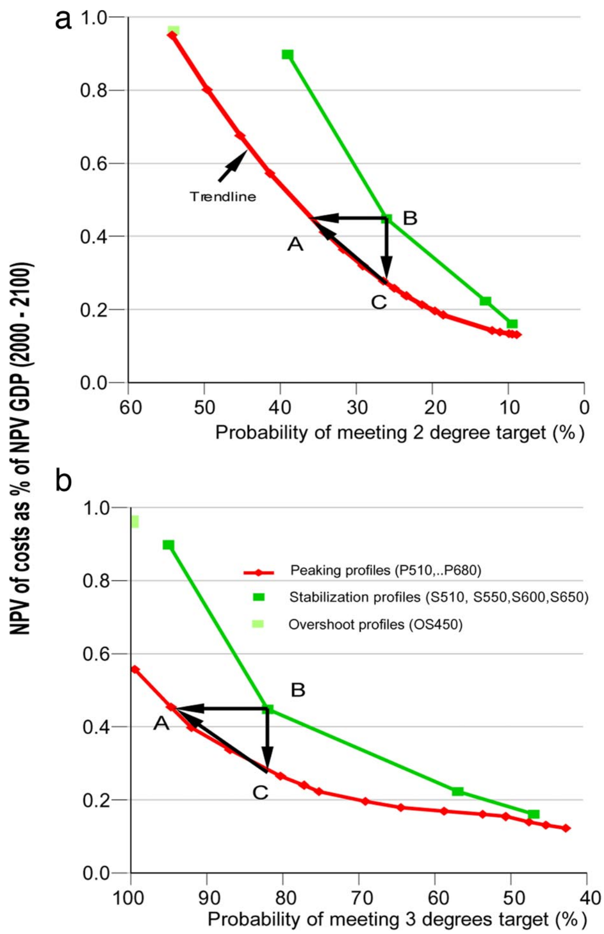

Fig. 5. NPV of abatement costs as a function of the probability to meet the 2°C (*a*) and 3°C (*b*) targets for the baseline B2 scenario. The circles represent the calculated outcomes of the peaking profiles (from 510 to 680 ppm at 10-ppm intervals), and the bold red line represents the trend line. The OS450 profile is shown here (green squares) for comparison. The squares represent the stabilization runs at 510, 550, 600, and 650 ppm CO_2-equivalent concentration. A, B, and C refer to P550, S550, and S580, respectively.

GHG concentration needs to be reduced further). Fig. 4*c* includes the results for the peaking profiles as well and shows that peaking profiles can increase the likelihood of achieving temperature targets at similar cost levels (proceeding horizontally from the green line to the red line). For example, stabilization at 550 ppm (Fig. 5*a*, B) would have a probability of ≈26% of meeting the 2°C target, for which the probability increases to 34% for peaking at 550 ppm (Fig. 5*a*, A). A similar trend is showed in Fig. 5*b* for meeting a temperature target of 3°C. Fig. 5 also can be read in a different way: for each stabilization point, there is a point associated with a peaking profile with the same likelihood of achieving a certain target but at lower costs, which corresponds to moving vertically from the green line to the red line. For example, arrow B to C (Fig. 5) shows that stabilization at 550 ppm versus peaking at 580 ppm reduces the NPV of the costs from 0.45% to 0.27%, ≈40%, without affecting the likelihood of achieving the 2°C target. These profiles thus can lead to achieving temperature thresholds with higher probability at lower abatement costs. More specifically, any point between C and A, i.e., peaking between 580 and 550 ppm, reduces the abatement costs and increases the likelihood of achieving the 2°C target (Fig. 5*a*).

The results depend on the discount rate. Peaking profiles include a greater reduction effort beyond 2100 and, therefore, lower discount rates raise costs of peaking profiles more than costs of stabilization profiles. In SI Fig. 8, we analyzed how a low, time-dependent discount rate would impact our findings. These results show that the cost benefits of peaking profiles become less but certainly do not disappear. Peaking profiles also come at a cost, i.e., somewhat higher transient temperature increase of profiles with a limited overshoot. The rate of temperature increase of stabilization profiles and the corresponding (lower costs) limited overshoot profiles are analyzed in SI Fig. 9. In each case, consequences for the rate of temperature increase seem to be limited. Similarly, the 2050–2100 temperature increase for the overshoot 580 ppm profile is ≈0.2°C higher than the temperature increase for the stabilization 550-ppm profile.

Conclusions and Discussion

We have explored the tradeoffs between the probability of reaching selected certain temperature thresholds and the abatement costs of emission reductions needed for a wide range of emissions pathways associated with peaking and stabilization of GHG concentrations. Our findings demonstrate that concentration peaking profiles, compared with their stabilization counterparts, can prevent some of the temperature increase beyond 2100 and thereby increase the probability of achieving long-term temperature targets. Although this requires higher emission reductions after the concentration peaks (beyond 2100), discounting implies, in most cases, relatively low additional costs if expressed as NPV. As a result, it also is possible to identify peaking profiles that meet long-term temperature targets for a given probability at lower costs. The reduction of the costs can be as much as 40%. These peaking and overshoot profiles use the climate inertia to obtain their climate and costs benefits. In our calculations, we assumed a high discount rate of 5%. At lower discount rates, the benefits discussed become smaller (see *SI Text*).

The analysis thus shows that if a temperature target is selected, there is no compelling reason for focusing only on stabilizing GHG concentrations; peaking strategies might be more attractive as part of the residual warming can be avoided. Because of these benefits with respect to climate and abatement costs, the consideration of concentration peaking in the 21st century, rather than only stabilization, is worthwhile from a scientific and from a political perspective; this is taking into account that the peaking concentration level determines the probability of meeting temperature targets. Frame *et al.* (27) used yet another argument forward in favor of peaking and overshooting instead of stabilization: namely, peaking warming scenarios can benefit from the fact that transient temperature change is less uncertain than long-term climate response. The implications of these peaking and overshoot peaking strategies as opposed to stabilization strategies are still the subject of ongoing research, but it is clear that such strategies can increase the feasibility of achieving stringent long-term climate targets.

However, it finally should be noted that these gains come at a cost: overshoot peaking profiles induce a higher rate of temperature increase and risks of high costs if we have to aim at lower levels. Increases in the rate of temperature change, however, are relatively small if overshoot is kept limited.

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