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New Research Suggests that Emissions Reductions May Be a Risky and Very Expensive Way to Avoid Dangerous Global Climate Changes

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New Research Suggests that Emissions Reductions Are a Risky and Very Expensive Way to Avoid Dangerous Global Climate Changes

Alan Carlin

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Abstract:

Proponents of greenhouse gas emissions reductions have long assumed that such reductions are the best approach to global climate change control and sometimes argued that they are the least risky approach. It is now generally understood that to be effective such reductions would have to involve most of the world and be very extensive and rapidly implemented. This paper examines the question of whether it is feasible to use only this approach to control dangerous global climate changes, the most critical of the climate change control objectives. I show that in one of two critical cases analyzed recent papers provide evidence that such an approach is not a feasible single approach to avoiding the dangerous climate changes predicted by a very prominent group of US climate change researchers. In the other case using a widely accepted international standard I show that such an approach appears to be very risky and much more expensive than previously thought. These conclusions further reinforce previous research that emissions reductions alone do not appear to be an effective and efficient single strategy for climate change control. So although emissions reductions can play a useful role in climate change control, other approaches would appear to be needed if dangerous climate changes are to be avoided. This conclusion suggests that the current proposals in a number of Western European countries and the United States to use emissions reductions as the sole means to control global warming may be doomed to failure in terms of avoiding such dangerous changes. An alternative approach is briefly discussed that would be more effective and efficient, and could avoid the perilous risks and high costs inherent in an emissions reduction only approach.

Keywords: Global warming control, global climate change control, implementation

Subject areas: Climate change, environmental policy, institutional issues: general

Fundamental to a rational decision as to what to do about global climate change is what the problems are that need to be solved and what and how much needs to be done how soon to solve them (*1*). It is sometimes forgotten that the objective of global climate change control should not be to reduce emissions of greenhouse gases (GHGs) but rather to reduce specified risks resulting from climate change. Previous research has shown that the very widely proposed approach of reducing emissions of GHGs is not likely to be either effective or efficient in reducing the risk of dangerous climate changes or some of the other goals of climate change control (1). Of four such risks previously identified (1), the most critical one is dangerous climate changes.

In order to investigate the feasibility of using an emissions reduction approach in reducing the risk of dangerous climate changes, it is necessary to define either the threats that we are trying to avoid or the goals that if achieved would avoid the threats since different threats may require different solutions. For this purpose I have defined two such threats/goals, representing two of the most prominent ones discussed in the literature. Obviously there may be other threats/goals, but a useful approach should at least control the most prominent ones unless we know for certain that another threat is the only one that will occur.

One of the threats, which I will call the Greenland/West Antarctica ice sheet melt, has been proposed by a prominent group of American climate scientists, usually with James Hansen as the lead author. Two new papers on the subject are by Hansen et al; both concern the risks from additional global warming as a result of sea level rise due to melting ice sheets in Greenland and West Antarctica. The first paper (*2*) argues that there are dangerous risks if global temperatures rise more than another $1^{o}C$ from current levels. The second (*3*) uses data from the last 400,000 years of Earth history to predict how and why they believe that sea levels may rise significantly over this century and to quantify key parameters including much higher climate sensitivity to increased carbon dioxide (CO_2) levels. A third paper with Hansen as the sole author (4) summarizes other research showing that the Greenland and West Antarctic ice caps are eroding, including speculation that the resulting sea level rise could be as much as 5 meters by 2100. *New Scientist* describes the consequences as follows (5):

> Without mega-engineering projects to protect them, a 5 meter rise would inundate large parts of many coastal cities--including New York, London, Sydney, Vancouver, Mumbai, and Tokyo--and leave surrounding areas vulnerable to storm surges. In Florida, Louisiana, the Netherlands, Bangladesh and elsewhere, whole regions and cities would vanish. China's economic powerhouse, Shanghai, has an average elevation of just 4 meters.

The long standing concern about dangerous climate changes is that there may be a "tipping point" where a continued rise in global temperatures will trigger non-linear, self-reinforcing further warming or other dangerous environmental effects beyond those resulting immediately from the temperature rise itself. Numerous scenarios have been proposed (*1*), but Hansen et al. believe that the most likely and most critical of these dangerous effects is the possibility of substantial sea level rise due to the breakup of parts or all of the ice sheets covering Greenland and West Antarctica. Taken together, Hansen et al (*2, 3,* and *4*) paint a rather alarming forecast of what they view as the dangerous effect of global warming is as they see it. Their words could not be more much more graphic or stark in their description of the risk they believe we face:

> "Our concern," Hansen et al. (*3*) write, that business as usual greenhouse gas scenarios "would cause large sea-level rise this century…differs from estimates of the IPCC (2001, 2007), which foresees little or no contribution to twenty-first century sea level raise from Greenland and Antarctica. However, the IPCC analyses and projections do not well account for the nonlinear physics of wet ice sheet disintegration, ice streams and eroding ice shelves, nor are they consistent with the palaeoclimate evidence we have presented for the absence of discernable lag between ice sheet forcing and sea-level rise." "Civilization developed," Hansen et al. say ominously "and constructed extensive infrastructure, during a period of unusual climate stability, the Holocene, now almost 12000 years in duration. That period is about to end."

Hansen et al., however, believe that their concerns can still be met through reductions in emissions of both CO_2 and the other GHGs, but they do state that they believe we are now at the outer limits of what can still be done to prevent the catastrophe that they predict will otherwise occur.

In the second case, the threat/goal is derived from the conventional United Nations Framework Convention on Climate Change (UNFCCC) and the announced policy by the European Union (EU) as to how it should be implemented. The ultimate goal of climate change control, the UNFCCC has declared, is to avoid dangerous climate changes. This has generally been interpreted as a temperature ceiling that if observed would accomplish this. The EU has explicitly adopted a limit of 2^{o}C above pre-industrial levels (*6*) and Germany, Britain, and Sweden have implicitly accepted it (7). These four Western European jurisdictions have all proposed implementing it, however, in ways that are unlikely to achieve the 2^{o}C limit (*7*), possibly because they appreciate the difficulty of meeting it. California, however, has used the limit as the basis for its climate change control legislation, as have some of the bills that have been proposed in Congress. The history and scientific basis for the 2^{o}C limit is briefly summarized in Hansen, et al. (*2*) and more extensively in Rive et al (*8*). Others have also suggested that a 2^{o}C warming is not likely to be safe (9) (*10*) (*11).*

A recent paper by Rive et al. (8) analyzes a range of possible limits on the rise in global temperatures to determine the near-term emission reductions needed to realize them using a variety of climate change parameters. This paper primarily uses their methodology as a framework by which to assess the feasibility of an emissions control approach to global climate change control in terms of limiting temperature increases to the levels specified in each of the two threat/goal scenarios just outlined. More specifically, the two cases are:

(A) <u>Greenland/West Antarctica ice sheet melt:</u> Hansen et al are assumed to be correct that climate sensitivity to increased levels of CO_2 is approximately 6^{o}C for a doubling of CO_2 (3) as well as their belief that there is substantial risk of a dramatic sea level rise if global temperatures increase more than another 1^{o}C (2).

(B) EU 2^{o}C Temperature Limit: There is assumed to be a substantial risk of dangerous climatic changes if global temperatures exceed 2^{o}C above pre-industrial levels. This is a little less strict than the second half of (A) since a further increase of global temperatures of 1^{o}C would be roughly consistent with a 1.8^{o}C increase from pre-industrial levels.

(A) Why an Emissions Control Only Strategy Would Not Be Useful if Hansen et al. Are Correct

As summarized in the quote above, Hansen et al (3) are arguing that the IPCC failed to take into account several non-linear factors that they believe will result in a much more rapid disintegration of the Greenland and West Antarctic ice sheets, which will in turn result in a much more rapid than predicted rise in global temperatures due to the resulting decreased albedo. Only by taking into account these factors, they argue, is it possible to explain the observed changes in climate over the last 400,000 years of repeated ice ages. They point out that the terminations of each of the Ice Ages during this period occurred very rapidly and that this observation needs to be taken into account in any explanation.

So the situation is that Hansen et al. predict a catastrophic rise in sea level if temperatures rise more than 1.8^{o}C over pre-industrial levels but claim that by stringent regulation of CO_2 and the trace GHG gases it is still possible to avoid it, but do not explain exactly how this can be actually done. The immediate question is whether their claims that emissions controls could be just sufficient to solve the sea level rise threat they perceive are credible. This is where Rive et al.'s paper is particularly relevant. The larger question is whether the world should plunge ahead with a reliance on what I will call exclusive regulatory de-carbonization (ERD) given that the risk of catastrophe appears to be very large according to Hansen et al.'s analysis and the costs very high as well?

By ERD I mean exclusive reliance on the reduction of greenhouse gases (GHGs) emitted into the atmosphere. This is intended to include governmental actions that are coordinated between nations (such as under the Kyoto Protocol) or done independently by each country or state or other political jurisdiction. It is also intended to include almost all of the current popular ideas, including "cap and trade," carbon taxes, fuel economy standards, bio-fuel subsidies, direct regulation, etc.

If Hansen et al. are correct, the ERD strategy proposed by many environmental groups, California, some Western European governments, and others would appear to be rational only if ERD could avoid dangerous climate changes. If not, this approach is likely to result in the dangerous global climate changes that these groups/governments and the UNFCCC are most concerned about. These four new papers taken together suggest that ERD is not just ineffective and inefficient, but would also not be a feasible approach to avoid ice sheet melting. Hansen et al. (*3*) are arguing that the real climate sensitivity is roughly double (*12*) that assumed by the IPCC (*13*), which would bring it to about 6^{o}C for a doubling of CO_2. The implementation feasibility diagrams presented by Rive et al. show that the use of a 2^{o}C temperature limit above pre-industrial temperatures and a 6^{o}C sensitivity lies so far outside the implementation possibilities they found as to be unachievable (see (14) and Table 1).

(B) Why an Emissions Reduction Only Strategy Would Still Be Very Risky and Expensive Even if Hansen et al. Should Prove to Be Wrong

Even if climate sensitivity to increased CO_2 is what the IPCC says it is, the modeling work by Rive et al (*7*) suggests that it would not only be risky but also very expensive to actually achieve the 2^oC limit using ERD. They find that to obtain a mere 50 percent chance of preventing more than a 2^oC increase would require a global cut of 80 percent from current industrial emission levels by 2050 at a marginal cost of $3,500 per ton of carbon equivalent assuming average projections and "early action" to reduce GHGs (see (15) and Table 1 below). $3,500 is roughly an order of magnitude or higher than most previous estimates of marginal costs (1), presumably reflecting the extremely high cost of rapidly replacing most of the energy producing and using capital stock. An 80 percent cut would imply a reduction per person of about 87 percent below current levels because of predicted world population growth, and appears of very doubtful practicality, particularly at the extremely high marginal costs estimated by Rive et al. and a mere 50 percent chance of "success" even in the "ideal" world of modeling. This suggests that in the real world a serious effort to achieve such cuts would be extremely expensive, require worldwide cooperation and an early start, and be much more likely to lead to catastrophe than success. Worst of all, it would probably postpone serious efforts to develop other approaches that would be more likely to succeed (*1*). Rive et al. furthermore find that if we wait an additional ten years to implement serious emissions reductions, a 50 percent chance would not be achievable at all, again assuming "average" projections (*16*). For a 75 percent probability (which would seem the least that humans might want to aspire to given the stakes involved) and early action, the researchers find that the target of 2^oC is also not achievable (15). A 75 percent probability could be achieved if one accepts "low" projections (15), but still at a very high marginal cost ($1,400 per ton of carbon equivalent). It appears very unwise, however, to gamble the fate of the world's climate on the lowest projections. It may be unwise to gamble it even on "average" projections. Using a "high" estimate, however, the best that can be achieved is a 25 percent probability at a marginal cost of $3,500 per ton of carbon equivalent! The apparent implication is that even under a 2^oC limit and 3^oC sensitivity ERD is a very long shot with little real hope of meeting the 2^oC limit even before taking into account the wide gap that is almost certain to exist between what is actually achieved and what countries or others may agree to do.

Analysis of Major Parameters

The Rive et al. paper uses a number of factors or parameters (which I have labeled P1, P2, P3, and P5) in determining the feasibility of emissions reductions to meet several alternative temperature limits. In addition there is a need to enhance their analysis by adding an additional parameter (P4) in order to make the analysis correspond better to the real world where the final outcome of ERD implementation can never be fully known in advance but instead must be based on expectations of future implementation of proposed mitigation measures. It should be noted that this added parameter by itself does not change the conclusions in the two cases examined, although it certainly reinforces them.

In order to escape the above conclusions concerning the limited usefulness of ERD in each case one presumably must believe that ERD meets tests concerning all of the following parameters (see Table 1 below and the footnotes to it):

(P1) Climate sensitivity to increased CO_2. To meet the test of this parameter in Case A it would be necessary to assume that sensitivity is less than about 3.1°C assuming a 2°C limit. In other words, reliance on ERD approaches depends critically on the assumed CO_2 sensitivity. Even if one believes that Hansen et al.'s 6°C is too pessimistic, one must believe that the sensitivity is no more than about 3.1°C in order to fall within Rive et al's possibilities curve. Hansen et al. clearly believe that the IPCC failed to take into account very significant factors that the IPCC may not have known about at the time since the Hansen et al. paper was not published until almost a year after the IPCC deadline. Just because the majority of the IPCC reviewers held a different view at that time does not make Hansen et al. incorrect, however. In Case B Rive et al.'s analysis assumes that P1 is about 3°C, so Case B meets this test.

(P2) Maximum global temperature increase that avoids a substantial risk that there will be a dangerous climate change if global temperatures increase more than that amount. The higher the maximum, the easier it is to meet it. In Case A, it would be necessary to believe that ERD could reduce the increase to no more than a further 1°C (1.8°C above pre-industrial levels) to avoid the large increase in sea level predicted by Hansen et al. (2). This is actually significantly more stringent than the requirement of less than 2°C in case B. But since Rive et al did not consider 1.8°C, it will be (charitably) assumed here that meeting the 2°C limit, which they do show, is the equivalent of meeting 1.8. With this assumption, ERD satisfies this test for both cases.

(P3) Relation of case to error bounds defined by Rive et al. It is assumed here that Rive et al.'s analysis is as valid as is currently possible. Under Case A in order for the conclusion not to hold it would be necessary to believe that the results of using a 1.8°C limit with Hansen et al.'s doubled temperature sensitivity to CO_2 falls on or inside the implementation possibilities curve for this temperature limit, which it comes nowhere close to doing (14). In case B the average probability estimates does fall on the implementation possibilities curve for 2°C limit and early "action" so it does qualify.

(P4) The ratio of actual emissions reductions that would be achieved in the real world application of ERD to the optimized reductions assumed by the modeling studies that Rive et al used to derive their results. This is not part of Rive et al.'s analysis but has been added to make the analysis more realistic since this is likely to be a major problem with actually implementing ERD in the manner that may be agreed to (1). Rive et al. effectively assume that the ERD efforts are as successful in reducing the risk of global warming as the underlying studies they use assume they are with the exception that they differentiate between "early" and "late" action. Since these studies effectively assume 100 percent success (a ratio of 1), Rive et al. do as well. There is ample reason to believe, however, that the real world implementation of whatever measures may actually be decided on to implement ERD will fall well short of the ideal cases assumed by the underlying studies for a number of practical reasons (1) taking into account that the Rive et al. analysis will really only be useful before a decision is made as to how to implement climate change control. If, for example, implementation should be carried out through an extension of the Kyoto Protocol, P4 would be the ratio of actual reductions achieved worldwide to the reductions agreed to in the extension worldwide. Although the period of performance of the current Protocol is not yet over, it is already clear that the ratio will be much less than 1.0 when it is completed (1). More generally, the history of compliance with voluntary international agreements (such as the failed Kellogg-Briand Pact of 1928), assuming that an effective one dealing with climate change control is eventually negotiated, is not very good. And the history of independent national objectives (such as for ending poverty or other types of pollution) is not much better. Given the record of the Kyoto Protocol to date, the fact that most of the world's governments and people would have to cooperate to make any ERD approach actually work, the difficulties politicians would have in convincing or requiring people to actually give up energy services that they have long enjoyed or even to pay higher costs for energy conservation, and the strong factors working in the opposite direction such as population and economic growth and the rapid spread of energy-using consumer electronics (*17*), are just a few of the factors that make it hard to believe that P4 would be very large (*1*). And there is every reason to believe that it would be quite small. Thus far the only real experience has been in the participating countries listed in Annex I of the Kyoto Protocol and perhaps in California. Of these, perhaps Great Britain and California may have tried as hard or harder than most. In both cases the result to date has been that emissions have remained roughly unchanged in recent years. This is actually an accomplishment given population and economic growth and rapid growth in the use of consumer electronics. But assuming past experience were relevant for determining P4, in these two cases P4 would currently be roughly 0 since no real decrease in emissions has occurred. Now it is possible that more might be accomplished by a more aggressive ERD effort such as is now proposed by some, but that is far from clear for the reasons just mentioned. To change the conclusion in Case B it would be particularly necessary to believe that the ratio is very high since it would have to be in order to achieve even the probabilities shown by Rive et al.'s analysis. So it is extremely unlikely that this parameter could be used to change the conclusions with regard to the usefulness of ERD in this Case.

(P5) <u>The cumulative probability as defined by Rive et al.</u> This is the probability that a given temperature limit will be achieved given the variability in the underlying studies used. An important issue is what the minimum probability society would find acceptable if it were to undertake a serious effort at climate change control and below which it would not want to pursue a particular control approach given the sacrifices involved. In case A the actual probability shown by Rive et al.'s analysis is 0, which is clearly unacceptable. But in Case B this probability is more crucial since Rive et al. shows that under ideal circumstances there is a 50 percent probability of achieving a 2^{o}C limit. Given the gravity of the possible consequences and the sacrifices involved, I believe that 50 percent is much less than citizens would be willing to accept if carefully polled, but this is a matter of judgment. 90 percent would appear more reasonable, but no "acceptable" number above 50 percent leads to an unchanged conclusion.

The conclusions from this analysis are that ERD fails in Case A because four of five parameters fail. In Case B, ERD fails unless a probability of 50 percent is acceptable (in P5) and the achievement ratio (P4) is much higher than it is likely to be. Even so, it would be extremely expensive according to Rive et al. (15).

The Alternatives

There would appear to really be only three basic options and several combinations thereof available for dealing with global climate change (1): Adaptation, ERD, and geoengineering—or as it is sometimes called in this case, solar radiation management, stratospheric geoengineering, or engineered climate selection. Case A suggests, however, that ERD is not a useful option for solving climate change problems (although it can still be helpful) if the primary purpose of climate change control is to avoid dangerous climatic changes and Hansen et al. are correct. Even if Hansen et al.'s threat analysis is wrong, case B suggests that ERD is still unlikely to be successful in meeting the 2^oC temperature limit.

This raises the interesting question of which threat/goal (A or B) any ERD effort should aim to satisfy? One can argue that the answer does not matter since neither one will be satisfied by the use of ERD if this analysis is correct. But the question is still of intellectual interest. I believe the answer is A for the following reason: Suppose A turns out to be the real threat. If we only do enough to satisfy B, we will have a situation where the world will have spent many trillions of dollars and much valuable time and failed to accomplish the goal of avoiding the real threat (A) and will as a result also have to bear the resulting adaptation costs (like moving major cities inland). On the other hand, if we do enough to satisfy A, we are also assured of avoiding the threats which B is intended to deal with. We may have spent more than we needed to, but we would have solved the problem and avoided the worst of the adaptation costs.

Climate change control needs to have other goals as well (*1*), but avoiding dangerous climate changes is surely the most immediate and critical one. As previously concluded, geoengineering appears to be the best single option (1) taking all the goals into account. If ERD cannot offer a high degree of assurance of accomplishing the fundamental goal of avoiding a substantial risk of dangerous climatic change, that would appear to leave various combinations of ERD, adaptation, and geoengineering as the only remaining options for this purpose.

In considering whether to abandon ERD as the proposed solution, an important issue concerns the problem of ocean acidification, another of the climate change problems that the world may wish to address (*1*), and which cannot be addressed using atmospheric geoengineering. The Royal Society (*17*) has expressed considerable concern about the fate of coral reefs and other sea life containing calcium carbonate in acidifying oceans. Caldeira (*19*) has recently stated that the reefs and other organisms can really only be saved by avoiding almost any further CO_2 emissions since he believes any net emissions will have an adverse effect. He has suggested a 98 percent reduction from current emission levels (*20*), apparently assuming that other natural forces reducing atmospheric

CO_2 levels might counteract the remaining 2 percent. The Royal Society report and Caldeira cite the high cost and practical difficulties of geoengineering approaches toward mitigating the chemical effects of increased atmospheric CO_2 concentrations on the oceans (*21*). But as noted in (*1*), decreasing CO_2 emissions will be a difficult and at best a very slow undertaking. Reducing them by 98 percent does not appear to be within the realm of realistic possibility in the current world, and probably falls well outside the bounds of the achievable if Rive at al. were to analyze this case. But not reducing CO_2 emissions will result in the extinction of the world's coral reefs, Caldeira argues (*22*). Surely before this is allowed to happen it would be worthwhile to carefully reexamine all available ocean geoengineering options, including those rejected by the Royal Society and Caldeira, since here too these would appear to be the only realistic options available that might satisfy the Royal Society's and Caldeira's concerns as to the effects of ocean acidification.

Although nature long ago demonstrated that there are atmospheric geoengineering options that could be effective in controlling global temperatures (*1*) (*23*) and meeting the 2^oC limit or any other desired temperature limit, no real effort has been made to optimize these options, carefully determine their non-climate change environmental effects, nor build an international mechanism for decision-making to implement them (*24*) despite the much lower costs (3 to 5 orders of magnitude) compared to de-carbonization and the fact that one country with the required technological and financial resources could if necessary implement such a solution directly without involving other countries or people once a decision had been made to proceed (*1*). Numerous arguments both for and against using atmospheric geoengineering have been debated for years, but often hinge on a metaphysical issue of whether humans should alter emissions to alter climate or alter global temperatures directly (*1*) (*25*). One possibility is a combination of early geoengineering to avoid any danger of dangerous climate changes with cost-effective ERD involving increasing energy efficiency but not decreasing energy services. Lack of preparation and support for using geoengineering approaches may prove to be unfortunate since the result is likely to be expensive but ineffective ERD and extensive adaptation. And if Hansen et al. and Caldeira are correct, the resulting adaptation currently appears likely to include adaptation to "dangerous" climate changes and the loss of the world's coral reefs.

The first step towards an effective and efficient response to global climate change would appear to be to carefully examine each of the problems posed by global climate change and to determine the best solutions to each problem (see *1*) rather than offering a single panecea (ERD) that appears to have critical limitations as an overall solution. The second step appears to be to carry out the needed development and also to develop a decision-making process for better using atmospheric geoengineering, and the third is to carefully research and attempt to find workable solutions to ocean acidification, including consideration of the use of ocean geoengineering. Continuing down a path towards ERD, if Hansen et al. are correct, will apparently not avoid dangerous climate changes, or if he is not, would still be very risky, very expensive, and probably disastrous in the end.

Table 1: Analysis of Major Parameters to Determine Feasibility of Using a Regulatory De-carbonization (RD) Only Approach to Control Dangerous Global Climate Changes

Parameters	(P1) Temp. sensitivity (°C)	(P2) Temp. limit (°C)	(P3) Relation to Rive sensi-tivity bounds	(P4) Real world achieve-ment ratio	(P5) Probability of achievement of limit (%)
Case A—Hansen et al. correct on risk of Greenland/West Antarctic ice sheet melting if P2>1.8°C					
A.1.Actual/assumed	6	1.8	Well outside high estimate	Very low	0
A.2.To accept RD	≤3.1	≤1.8	Meets average projection	Very high	≥90
A.3.To reject RD	>3.1	>1.8	Outside high estimate	Medium to low	<90
A.4.Conclusions concerning RD	Fails	Meets using 2°C	Not achievable	Fails	Fails
Case B—EU correct that global temperature rise should be no more than 2°C					
B.1.Actual/assumed	3	2.0	Meets average projection	Very low	50
B.2.To accept RD	≤3.1	≤2.0	Meets average projection	Very high	≥90
B.3.To Reject RD	>3.1	>2.0	Outside high estimate	Medium to low	<90
B.4.Conclusions concerning RD	Meets	Meets	Meets	Fails	Meets if 50% acceptable; fails if accept-able P5≥51

<u>Sources:</u>
Column P1: Row A.1: Reference (12); Rows A.2, A.3, B.2, and B.3: Based on visual reading of (14); Row A.4: Comparison of Row A.3 with A.1; Row B.1: Approximation of IPCC estimate (13); Row B.4: Comparison of Rows B.2 and B.1.

Column P2: Rows A.1, A.2, and A.3: Hansen et al.'s 1°C increase over current (2) plus approximation of 0.8°C current over pre-industrial temperatures since this is an optimistic assumption; Row A.4: Comparison of Rows A.3 with A.1. Rive et al. analyzes 2°C, but not 1.8, so it is assumed (optimistically) that the two are the same for the purposes of this cell; Row B.1: See text for explanation of selection of 2.0°C; Rows B.2 and B.3: EU policy (6); Row B.4: Comparison of Row B.2 with B.1.

Column P3: Rows A.1, A.2, A.3, B.1, B.2, and B.3: Based on (14) using black sensitivity probability lines, 2^{o}C limit, and 2025 peak; Row A.4: Comparison of Row A.3 with A.1; Row B.1: Also based on (11); Row B.4: Comparison of Rows B.2 and B.1.

Column P4: Rows A.1, A.2, A.3, B.1, B.2, and B.3: See discussion concerning column P4 in main text of this paper; Row A.4: Comparison of Row A.3 with A.1; Row B.4: Comparison of Rows B.3 and B.1.

Column P5: Row A.1: (15); Rows A.2, A.3, B.2, and B.3: Guesstimate as described in text; Row A.4: Comparison of Row A.3 and A.1; Row B.1: (11). Row B.4: Comparison of Row B.3 and B.1. This conclusion holds as long as B.3 is greater than in Row B.1, regardless of the 90 percent guesstimate used for B.3.

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15. Rive, et al., *op. cit*, Table 1. 1.8 GtCeq is about 80 percent of year 2000 emissions shown as 9.1 GtCeq in the footnote to Table 1. In this and all their other cases, Rive et al. (*4*) assume that there will be no overshooting because they believe that overshooting might compromise the overall objective. Their term 'overshoot' refers to when a scenario exceeds a given target (i.e., temperature) for a short period of time as a result of climate system inertia, before eventually returning to the target level.
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