A cost-effectiveness metric for climate mitigation policy

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Abstract

A generalized global warming function derived from climate sensitivity estimates provided by the Intergovernmental Panel on Climate Change determines the quantum of global warming that would be forestalled by any given reduction in carbon dioxide concentration. The function assists in assessing the cost-effectiveness of policies intended to mitigate anthropogenic global warming through regulation of the combustion of fossil fuels. Several case studies demonstrate that policy measures to mitigate global warming that are limited enough to be affordable are ineffective, while measures radical enough to be effective are unaffordable. Any attempt at mitigation is likely to prove cost-ineffective, particularly when set against the later and lesser costs of focused adaptation.

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Introduction

How much anthropogenic global warming will any given policy to address that warming forestall? Answering this question is an essential first step in determining the cost-effectiveness of proposed carbon mitigation policies: yet the question has been largely unaddressed to date in the extensive literature on climate change. The Intergovernmental Panel on Climate Change (IPCC), in Solomon *et al.,* eds. (2007), estimates that, in response to a doubling of atmospheric CO_2 concentration, equilibrium climate sensitivity will be 3.26 ± 0.69 K (ch. 10, p. 798, box 10.2). However, the *Summary for Policymakers* (Solomon, *op. cit.*, p. 12) gives 3[2, 4.5] K, values outwith this interval being thought theoretically possible but unlikely. *Ad argumentum,* then, the two estimates in Solomon will be conflated:

$$\Delta T_{\text{equ}} \approx 3.25 \pm 1.25 \text{ K.} \qquad (1)$$

The equilibrium warming function and its derivation

In the IPCC's methodology, global warming ΔT_{equ} is the product of three variables:

- the radiative forcing $\Delta F = \alpha \ln(C/C_0)$ (Myhre *et al.,* 1998), defined by Houghton *et al.,* (2001: ch. 6.1) as the change in net solar plus long-wave radiance at the tropopause, in Watts per square meter, after stratospheric temperatures have readjusted to radiative equilibrium, with surface and tropospheric temperatures held unperturbed, where (C/C_0), the proportionate change in CO_2 concentration, equals 2 at any CO_2 doubling;
- the Planck climate-sensitivity parameter κ, expressed in Kelvin per Watt per square meter, that converts a forcing in W m^{-2} to warming in K where temperature feedbacks are net-zero (Solomon, Ch. 8., p. 631, footnote);
- the unitless temperature-feedback factor $f = (1 - b\kappa)^{-1}$ (Bode, 1945), which mutually amplifies the sum b in W m^{-2} K^{-1} of all positive (amplifying) and negative (attenuating) temperature feedbacks – additional forcings triggered by the initial temperature change wrought by the original forcing.

The product of κ and f, written λ, is the final climate-sensitivity parameter. Then the equilibrium warming function is

$$\begin{aligned} \Delta T_{\text{equ}} &= \lambda\, \Delta F \\ &= \lambda\, \alpha \ln(C/C_0) \\ &= n \ln(C/C_0) \end{aligned} \qquad (2)$$

The warming coefficient n is now derived. At CO_2 doubling, where $(C/C_0) = 2$,

$$\begin{aligned} \Delta T_{\text{equ}} &= n \ln 2 \\ &\approx (3.25 \pm 1.25) \text{ K} \end{aligned} \qquad (3)$$

Thus,

$$\begin{aligned} n &\approx (3.25 \pm 1.25) \,/\, \ln 2 \\ &\approx (4.7 \pm 1.8), \end{aligned} \qquad (4)$$

and

$$\Delta T_{\text{equ}} = n \ln(C/C_0) \quad | \quad (2.9 \le n \le 6.5) \qquad (5)$$

The generalized warming function

Next, Eq. (5), the equilibrium warming function, is generalized to take account of the difference between warming when the climate has returned to *equilibrium* and *transient* warming during some shorter period of study, here $10 \le y \le 100$ years. An additional term r_y represents the ratio of transient warming over y years to warming at eventual equilibrium. On the A2 emissions scenario that most closely approximates today's conditions, Solomon's central projection is a 0.2 K/decade *transient* warming in response to CO_2 forcing from 2000-2010, other anthropogenic forcings being broadly self-canceling. However, the observed increase in CO_2 concentration was 20 ppmv, implying *equilibrium* warming $4.7 \ln(388/368) \approx 0.25$ K over the decade, and hence a decadal transience ratio $r_{10} \approx 0.2/0.25 \approx 0.8$. From 2000-2100 (on the A2 scenario), with projected transient warming of 3.4 K and CO_2 concentration rising from a measured 368 ppmv in 2000 to a projected 836 ppmv in 2100, the centennial transience ratio $r_{100} = 3.4 / [4.7 \ln (836/368)] \approx 0.9$. Therefore, for periods $10 \le y \le 200$ years, this simplifying approximation is taken:

$$r_y \approx 0.79 + 10^{-3} y. \quad | \quad (10 \le y \le 200) \qquad (6)$$

For instance, $r_{10} \approx 0.8$, $r_{50} \approx 0.84$, and $r_{200} \approx 0.99$. Now Eq. (5) is generalized to yield *transient* warming where $0.8 \le r_y < 1$, and *equilibrium* warming where $r_y = 1$:

$$\Delta T = r_y\, n \ln(C/C_{\text{pol}}), \quad | \quad (10 \le y \le 200), (2.9 \le n \le 6.5) \qquad (7)$$

where C is the projected business-as-usual CO_2 concentration after y years, and C_{pol} is the lesser concentration after y years following implementation of a given policy to mitigate carbon emissions. For equilibrium climate sensitivity, r_y is taken as unity. Eq. (7), the generalized warming function, determines the quantum of transient or equilibrium global warming likely to be forestalled by any proposed policy to address anthropogenic climate change by mitigating carbon emissions. After some initial observations and data have been considered, several case studies will demonstrate the applicability of Eq. (7) in evaluating policy options.

Initial observations and data

In each case study, five values n = 2.9, 3.7, 4.7, 5.7, 6.5 of the coefficient in Eq. (7) will be applied, to encompass the range of climate-sensitivity estimates in Solomon.

Using the NOAA's method (Keeling *et al.,* 1976; Thoning *et al.,* 1989), atmospheric CO_2 concentration stands today at $C_0 \approx 390$ ppmv compared with $C_{\text{nat}} \approx 280$ ppmv in 1750, so that the anthropogenic component is currently 110 ppmv. It is assumed that all increases in CO_2 concentration since 1750 have been or will be anthropogenic, and that the entire anthropogenic component in CO_2 concentration since 1750 will be subject to any policy-driven reductions.

Emissions scenario A2 in Solomon, which most closely replicates observed emissions today, projects that CO_2 concentration will increase exponentially this century from $C_0 \approx 390$ ppmv in 2010 to $C_1 \approx 836[730, 1020]$ ppmv in 2100. On this assumption, where y is the term of years under study,

$$C \approx C_0 e^x \quad | \quad x = (y/90)\ln(C_1/C_0) \tag{8}$$

Decadal values of *C* determined using Eq. (8) are given in the first three rows of Table 0.

Though CO2 *emissions* are rising at the high end of the IPCC's projections, for more than a decade CO2 *concentrations* have been rising not at the exponential rate projected by the IPCC but at a linear 2 ppmv yr^{-1}. Therefore, additionally each policy option will be evaluated on the assumption that this merely linear rate of concentration growth will continue so that, in any year $1 \le a \le y$, $C = C_0 + 2a$, reaching 570 ppmv by 2100, as shown in the fourth row of Table 0.

Decadal values of the transience ratio r_y are shown at the foot of the table.

Year	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
y	0	10	20	30	40	50	60	70	80	90
Max.	390	434	483	537	598	665	740	824	917	1020
Cent.	390	424	462	503	547	596	648	706	768	836
Min.	390	418	448	481	515	552	592	635	681	730
+2/yr	390	410	430	450	470	490	510	530	550	570
r_y	0.79	0.80	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.88

Table 0. Projected CO2 concentrations *C* after $0 \le y \le 90$ years, in decadal increments, if CO2 concentration rises exponentially from $C_0 \approx 390$ ppmv in 2010 to reach $C_1 \approx 1020$, 836, or 730 ppmv respectively by 2100 (rows 1-3), or rises linearly at 2 ppmv/year from $C_0 \approx 390$ ppmv in 2010 to reach $C_1 \approx 570$ ppmv over the same 90-year period (row 4); with decadal values for the transience ratio r_y (row 5).

In Eq. (7), the CO2 concentration C_{pol} after *y* years of policy-driven reduction is dependent upon $C_{nat} \approx 280$; upon *C;* and upon the fraction *p* of global anthropogenic emissions reduced after *y* years, thus:

$$C_{pol} = C - p(C - C_{nat}). \tag{9}$$

Case study 1: Close down the United Kingdom

The UK accounts for 2% of global emissions. In this first case study, the UK will be closed down stepwise, so that by 2050 all economic activities and carbon emissions have entirely ceased. Without the policy change, if CO2 concentration were to increase exponentially at the high end of the A2 scenario's projections in Solomon, 40 years from now CO2 concentration *C* would be 598 ppmv (table 0, row 1).

However, if the UK were shut down completely, reducing global emissions by 2%, then in 2050 C_{pol} would be 592 ppmv. From Table 0, row 5, $r_{40} = 0.83$. Finally, the high-end value $n = 6.5$ of the coefficient in Eq. (7) is taken. Then the maximum global warming forestalled by total shutdown of the UK 40 years from 2010 would be

$$\Delta T \approx 6.5\, r_y \ln(C/C_{pol}) \approx 6.5 \times 0.83 \ln(598/592) \approx 0.1\text{ K}. \tag{10}$$

Applying Eq. (7) *mutatis mutandis* to the full matrix of projected CO_2 concentrations and warming coefficients in Solomon, Table 1 shows that shutting down the UK would forestall very little global warming over the next four decades.

C	C_{pol}	n = 2.9	n = 3.7	n = 4.7	n = 5.7	n = 6.5
598	592	0.03 K	0.03 K	0.04 K	0.05 K	0.06 K
547	542	0.02 K	0.03 K	0.04 K	0.05 K	0.05 K
515	511	0.02 K	0.03 K	0.04 K	0.04 K	0.05 K
470	466	0.02 K	0.02 K	0.03 K	0.04 K	0.04 K

Table 1. Warming forestalled by closing down the UK stepwise over the 40 years 2010-2050, thereby cutting 2% of global emissions. The table shows CO_2 concentration C in 2100 with no policy change; CO_2 concentration C_{pol} in 2100 if the policy is implemented; and the global warming that the policy is projected to forestall.

Note that in this and other case studies, stepwise introduction of the policy measures and hence stepwise reductions in CO_2 concentration over the period of study would approximately halve the warming forestalled during the period: but in the longer term the warming forestalled would approach the values shown and, at eventual equilibrium, would slightly exceed them. Note also that the effects of any policy changes are assumed to be immediate, notwithstanding the contention in Solomon that the atmospheric residence-time of CO_2 is 50-200 years.

Case study 2: Wind-farms replace 5% of global electricity generation

It has been proposed that, where possible, wind power should replace fossil-fuel electricity, which will be assumed, generously, to account for 80% of all CO_2 emissions. However, if wind power contributes more than 5% to the generation mix, the grid becomes unstable because wind strength varies. Therefore, this case study assumes that no more than 5% of 80% – i.e. 4% – of global emissions will be replaced by wind-farms.

Three further generous assumptions are made: first, that the wind turbines will deliver at 100% of their rated capacity, when 20% is more usual; secondly, that there are no wind turbines operating at present; and thirdly, that the manufacture, vecture, installation, maintenance, regulatory/governmental overhead, and eventual decommissioning of the turbines emit no CO_2 at all.

Table 2 shows the global warming that would be forestalled by the wind-farm policy.

C	C_{pol}	n = 2.9	n = 3.7	n = 4.7	n = 5.7	n = 6.5
1020	990	0.08 K	0.10 K	0.12 K	0.15 K	0.17 K
836	814	0.07 K	0.09 K	0.11 K	0.14 K	0.15 K
730	712	0.06 K	0.08 K	0.10 K	0.13 K	0.14 K
570	558	0.05 K	0.07 K	0.09 K	0.11 K	0.12 K

Table 2. Warming forestalled over the 90 years 2010-2100 by replacing 4% of total global emissions with wind-farms. The table is calculated on the same basis as Table 1, with values of *C* at *y* = 90 taken from Table 0, and warming forestalled determined using Eq. (7).

Case study 3: Full Western compliance with the Copenhagen accord

The Annex 1 states parties to the UN Climate Convention account for half of all global emissions. To comply with their undertakings under the Copenhagen Accord, they must reduce their carbon emissions stepwise by 30% (i.e. 15% of global emissions) from 2010 to the Copenhagen reference date of 2020. It will be assumed, generously, that developed countries' emissions cuts will not be dwarfed by emissions growth in developing countries like China and India. Table 3 shows the warming forestalled:

C	C_{pol}	n = 2.9	n = 3.7	n = 4.7	n = 5.7	n = 6.5
434	411	0.13 K	0.16 K	0.21 K	0.25 K	0.28 K
424	403	0.12 K	0.16 K	0.20 K	0.24 K	0.27 K
418	397	0.12 K	0.15 K	0.19 K	0.23 K	0.26 K
410	390	0.11 K	0.14 K	0.18 K	0.22 K	0.25 K

Table 3. Warming forestalled by cutting 15% of global emissions in the Copenhagen reference decade 2010-2020.

Case study 4: Implement the Waxman-Markey cap-and-trade Bill fully

The US emits 20% of global CO2. The Bill tabled by Congressmen Henry Waxman and Ed Markey aims to phase out 83% of US CO2 emissions by 2050. The policy, if implemented fully, would thus reduce global emissions by 17% over the period. Table 4 shows the global warming forestalled if the Bill were fully implemented.

C	C_{pol}	n = 2.9	n = 3.7	n = 4.7	n = 5.7	n = 6.5
598	545	0.22 K	0.28 K	0.36 K	0.44 K	0.50 K
547	503	0.20 K	0.26 K	0.33 K	0.40 K	0.46 K
515	476	0.19 K	0.24 K	0.31 K	0.37 K	0.43 K
470	438	0.17 K	0.21 K	0.27 K	0.33 K	0.38 K

Table 4. Warming forestalled by implementing the Waxman-Markey cap-and-trade Bill in the US, cutting global emissions by 17% over the 40 years 2010-2050.

Case study 5: Developed countries halve emissions by 2050

Some have suggested that all Annex 1 states parties to the UN Climate Convention should phase out 50% of their emissions by 2050, representing a global reduction of 25% over the 40-year period. Table 5 shows the global warming that this policy would forestall.

C	C_{pol}	n =	n =	n = 4.7	n =	n =

		2.9	3.7		5.7	6.5
598	518	0.34 K	0.44 K	0.56 K	0.67 K	0.77 K
547	480	0.31 K	0.40 K	0.51 K	0.62 K	0.70 K
515	456	0.29K	0.37 K	0.47 K	0.57 K	0.65 K
470	422	0.26 K	0.33 K	0.42 K	0.50 K	0.57 K

Table 5. Warming forestalled by cutting 25% of total global emissions over the 40 years 2010-2050.

Case study 6: Developed countries cut emissions 80% by 2080

It has been suggested that Annex 1 states should cut their emissions stepwise to achieve 80% reductions by 2080, representing a 40% reduction in global emissions over 70 years. Table 6 shows the global warming that this policy would forestall.

C	C_{pol}	n = 2.9	n = 3.7	n = 4.7	n = 5.7	n = 6.5
824	606	0.76 K	0.98 K	1.24 K	1.50 K	1.71 K
706	535	0.69 K	0.88 K	1.12 K	1.35 K	1.54 K
635	493	0.63 K	0.81 K	1.02 K	1.24 K	1.42 K
530	430	0.52 K	0.67 K	0.85 K	1.02 K	1.17 K

Table 6. Warming forestalled by cutting 40% of total global emissions over the 70 years 2010-2080.

Case study 7: Solar power replaces half of generating capacity by 2100

Maximum solar saving is 50%: the sun does not shine at night. Phasing in solar stations from 2010-2100 would cut 50% of 80% of global emissions, or 40% in all, over 90 years. Ignoring transmission losses, and environmental harm in transmitting solar power to the night-side, Table 7 shows the global warming forestalled.

C	C_{pol}	n = 2.9	n = 3.7	n = 4.7	n = 5.7	n = 6.5
1020	724	0.87 K	1.12 K	1.42 K	1.72 K	1.96 K
836	614	0.79 K	1.01 K	1.28 K	1.55 K	1.77 K
730	550	0.72 K	0.92 K	1.17 K	1.42 K	1.62 K
570	454	0.58 K	0.74 K	0.94 K	1.14 K	1.30 K

Table 7. Warming forestalled by cutting 40% of total global emissions over the 90 years 2010-2060.

Table 8 summarizes the global warming that would be forestalled if the policies described in each of the seven indicative case studies were fully implemented.

Case study	Cut in global CO2 emissions	–1 standard deviation		Central IPCC est.		+1 standard deviation	
		A	B	A	B	A	B
IPCC warming to 2100	No cut by 2100	0.0 K	2.7 K	0.0 K	3.4 K	0.0 K	4.1 K
Total UK shutdown	2% cut by 2050	0.0 K	1.0 K	0.0 K	1.5 K	0.0 K	2.2 K

5% wind power	4% cut by 2100	0.1 K	2.6 K	0.1 K	3.3 K	0.1 K	4.0 K
Copenhagen Accord	15% cut by 2020	0.1 K	0.1 K	0.2 K	0.1 K	0.2 K	0.3 K
Waxman/Markey	17% cut by 2050	0.2 K	0.8 K	0.3 K	1.2 K	0.4 K	1.8 K
50% Annex 1 cut	25% cut by 2050	0.4 K	0.6 K	0.5 K	1.0 K	0.7 K	1.5 K
80% Annex 1 cut	40% cut by 2080	0.8 K	0.7 K	1.1 K	1.3 K	1.5 K	2.1 K
50% global solar	40% cut by 2100	0.9 K	1.8 K	1.3 K	2.1 K	1.7 K	2.4 K

Table 8. Global warming forestalled (A) and net warming projected after deduction of forestalled warming (B) in each of seven case studies, based on Solomon's central climate-sensitivity estimate ± 1 standard deviation, and on Solomon's central scenario-A2 estimate of exponential 21st-century CO_2 emissions growth.

Discussion

The simple, generalized global warming function that is here presented offers a necessary and accessible starting-point for determining the quantum of global warming forestalled by any given policy proposal, as a first step towards determining that proposal's cost-effectiveness.

The case studies, which on balance somewhat overstate the quantum of warming likely to be forestalled by policy measures to mitigate CO_2 emissions, demonstrate that regional-scale mitigation, such as shutting down the UK entirely even for as long as 40 years, would forestall very little global warming.

Global Annex-1 compliance with the Copenhagen Accord would prevent half of the global warming that might otherwise occur over the coming decade. However, that would make a small difference to global temperature, at very substantial cost.

It is only with drastically large-scale global mitigation over a long period – such as replacement of half of the world's electricity generating capacity by solar power over the rest of this century – that an appreciable quantum of long-run global warming would be forestalled.

Herein lies one of the two central economic problems posed by any policy of attempted global reduction in future emissions of CO_2. Any cut small enough to be affordable will have no measurable effect on the climate, while any cut large enough to have a measurable effect on the climate will not be affordable.

The second problem is that, as these results strongly suggest, focused adaptation to any global warming that may occur, as and if it occurs, would probably be orders of magnitude cheaper and more cost-effective than any attempt at mitigation, so that policymakers might in normal circumstances consider abandoning the mitigation pathway altogether. However, the IPCC was structured from the outset in such a way that mitigation and adaptation were considered in separate working groups. This is one reason why the relative costs and benefits of mitigation and adaptation have not been correctly evaluated in the literature to date.

Eq. (7) can be deployed to form the basis of a cost-effectiveness metric for competing policy options, measured in US dollars per Kelvin forestalled.

- Example 1: The UK's climate change Bill is officially projected to cost \$30 billion annually for 40 years, or \$1.2 trillion, but the maximum warming forestalled would be 0.06 K, giving a minimum cost of £22-57 trillion per Kelvin forestalled.

- Example 21: The US Government has officially estimated that the cost of implementing the Waxman-Markey Bill in full will be $180 billion annually during the four decades to 2050, by which time, in accordance with the target stated in the Bill, 83% of the US carbon economy will have been shut down. The officially-estimated total cost of the Bill will thus be $7.2 trillion, and the global warming forestalled would be at most 0.5 K, giving a minimum cost of £14.4 trillion per Kelvin forestalled – better value than shutting down the UK, but still disproportionately costly.

It is possible that the true costs of measures intended to mitigate global warming by regulating carbon dioxide emissions will be considerably above these already substantial values. If, for instance, climate sensitivity turns out to be at the lower end of the IPCC's projections, and if the atmospheric residence time of CO2 is as great as the IPCC considers it to be, then the cost per Kelvin of global warming forestalled in the two examples above will be more than double the values shown.

It has been determined theoretically (*e.g.* Lindzen, 2007; Schwartz, 2007; Monckton of Brenchley, 2008) and confirmed empirically by direct measurement of outgoing radiation from the Earth's characteristic-emission level (*e.g.* Lindzen and Choi, 2009, 2010 (submitted); Covey, 1995; Chen *et al.,* 2002; Cess & Udelhofen, 2003; Hatzidimitriou *et al.* 2004; Clement & Soden, 2005) and by direct measurement of ocean temperatures in the mixed layer (Lyman *et al.,* 2006 as amended, Gouretski & Koltermann, 2007, Willis, 2008, and Loehle, 2009, all show ocean cooling; Willis *et al.*, 2009, show no ocean warming); that the IPCC's current central estimate of climate sensitivity to atmospheric CO2 enrichment may be very substantially exaggerated. If so, a corresponding reduction in the coefficient n in Eq. (7) and consequently in the quantum of warming forestalled is mandated, increasing still further the cost per Kelvin of warming forestalled.

Conclusion

Given the very heavy cost of mitigation of CO2 emissions per Kelvin of warming forestalled that is indicated in the case studies, the later and lesser costs of focused adaptation to any climate change that may occur, and the fact that warming <2 K is regarded as beneficial or at least harmless, the probability that adaptation will prove significantly more cost-effective than any attempted mitigation is high.

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