Is CO2 mitigation cost-effective?

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Abstract

A much-simplified inter-temporal appraisal method using results from the Intergovernmental Panel on Climate Change (IPCC) permits non-specialist policymakers rapidly to obtain a first approximation of how much global warming a given CO2-mitigation policy may abate; the cash, per-capita, and global-GDP cost of abating all global warming to a target year by measures as cost-effective as the policy; the policy's mitigation cost-effectiveness in dollars per Kelvin abated; and the cost/benefit ratio. Case studies illustrating the method's utility in rapidly comparing competing policy options indicate that government projections tend to understate the cost of climate action and overstate the welfare loss from inaction. For example, at a market discount rate the global abatement cost of the Australian carbon tax is 48 times the welfare loss from inaction. Focused adaptation to any adverse consequences of global warming will prove more cost-effective than attempted mitigation. No policy will be cost-effective solely on grounds of the welfare benefit foreseeable from CO2 mitigation alone. Mitigation policies inexpensive enough to be affordable will be ineffective: policies costly enough to be effective will be unaffordable.

Keywords

Climate economics; abatement cost; mitigation cost-effectiveness

Introduction

Hitherto, economists have chiefly addressed the cost-effectiveness of climate mitigation globally. Here a much-simplified method, based on results of the Intergovernmental Panel on Climate Change (IPCC) that are taken as normative *ad argumentum,* is intended to enable even non-specialist policy-makers rapidly to estimate not only how much global warming any proposed CO2-reduction policy may be expected to abate but also, on the assumption that the cost-effectiveness of all mitigation strategies worldwide is equivalent to that of the policy, its global abatement cost (which is the cost of abating a given quantum of projected future warming by measures of equivalent cost-effectiveness) and its mitigation cost-effectiveness in US dollars per Kelvin of warming abated. Brief case studies compare the costs of competing CO2-reduction policies with one another and with published estimates of the welfare loss arising from unmitigated climate change.

As benchmarks, Stern (2006, p. vi), adopting an inter-temporal discount rate not exceeding 1.4%, estimates that the cost of abating the 3 K 21st-century global warming the IPCC expects will be 0-3% of GDP (mean 1.5%) and that 1% of 21st-century global GDP would suffice to abate 5 K global warming to 2100, against a global inaction cost of 5-20%, while Garnaut (2008, p. 253, fig. 11.2, & p. 270, table 11.3), projecting 5.1 K unmitigated global warming to 2100 and using a 1.35-2.65% discount rate, puts Australia’s 21st-century mitigation and inaction costs at 3.2-4% and 6% respectively. The economic literature puts the inaction cost at 1-4% of global 21st-century GDP and regards an inter-temporal discount rate of 5% as normative (e.g. Nordhaus, 2008; Murphy, 2008).

Warming beyond 2100 is not considered here. Since equilibrium temperature will not be reached for 1000-3000 years (Solomon *et al.,* 2009), it is centennial-scale transient warming that is policy-relevant today: subsequent warming will occur too slowly over the millennia to do unavoidable harm. Costs external to the policy and benefits external to mitigation of CO2 forcing are beyond the focus of this paper, but the method may readily be adapted to encompass them. Warming of 3 K and 3% uniform GDP growth in the 21st century are assumed: little error arises from assuming uniformity, and other rates may be chosen. A 5% discount rate is assumed on account of centennial-scale uncertainties, but lesser rates are also considered.

Projected 21st-century CO2-driven warming

Stern (2006) concluded that, though previous projections had indicated 2-3 K anthropogenic warming by 2100, causing a permanent global output loss estimated at 0-3% (mean 1.5%), more recent evidence suggested 5-6 K warming by the end of this century, and possibly 10-11 K warming by 2200.

However, IPCC (2007) presented estimates of radiative forcing and warming this century under six emissions scenarios (*op. cit.,* p. 18), to each of which it accorded equal weight. Taking their mean, a central estimate ΔT_{C21} of 21st-century warming is 2.8 K (Table 1), of which 0.6 K is already committed, so that the implicit central estimate of mean warming from 2000-2100 consequent upon all greenhouse-gas emissions since 2000 is 2.2 K, of which 70%, or 1.5 K, is CO2-driven.

Scenario	ΔT_{C21}	ΔT_{tra}	ΔF_{tra}	C_{2100}	λ_{tra}	$\Delta F_{tra,CO2}$	q
A1B	2.8 K	3.0 K	6.2 W m^{-2}	700 ppmv	0.5 K W^{-1} m^{2}	4.5 W m^{-2}	0.7
A1F1	4.0 K	4.5 K	9.1 W m^{-2}	960 ppmv	0.5 K W^{-1} m^{2}	6.2 W m^{-2}	0.7
A1T	2.4 K	2.5 K	5.1 W m^{-2}	570 ppmv	0.5 K W^{-1} m^{2}	3.4 W m^{-2}	0.7
A2	3.4 K	3.8 K	8.0 W m^{-2}	840 ppmv	0.5 K W^{-1} m^{2}	5.5 W m^{-2}	0.7
B1	1.8 K	2.0 K	4.1 W m^{-2}	520 ppmv	0.5 K W^{-1} m^{2}	2.9 W m^{-2}	0.7
B2	2.4 K	2.7 K	5.6 W m^{-2}	610 ppmv	0.5 K W^{-1} m^{2}	3.8 W m^{-2}	0.7
Mean	2.8 K	3.1 K	6.3 W m^{-2}	700 ppmv	0.5 K W^{-1} m^{2}	4.4 W m^{-2}	0.7

Table 1. Projected 21st-century anthropogenic warming ΔT_{C21} (IPCC, 2007, p. 13, Table SPM.3) and warming ΔT_{tra} and total radiative forcings ΔF_{tra} from all greenhouse gases for 1900-2100 on all emissions scenarios, and CO2 concentration C_{2100} in 2100 (IPCC, 2007, p. 803, Fig. 10.26); and, derived from these, the 200-year transient-sensitivity parameter $\lambda_{tra} = \Delta T_{tra}/\Delta F_{tra;}$ the CO2 radiative forcing $\Delta F_{tra,CO2} = 5.35 \ln(C_{2100}/C_{1900})$ from 1900-2100, taking C_{1900} as 300 ppmv; and the ratio $q = \Delta F_{tra,CO2} / \Delta F_{tra}$ of CO2 forcing to total greenhouse-gas forcing.

Table 1 shows that, on each scenario, the IPCC's estimate of the bicentennial-scale transient-sensitivity parameter λ_{tra} is 0.5 K W^{-1} m^{2}. IPCC (2001, p. 354, citing Ramanathan, 1985) took 0.5 K W^{-1} m^{2} as a typical climate-sensitivity parameter. Garnaut (2008) talks of keeping greenhouse-gas rises to 450 ppmv CO2-equivalent above the 280 ppmv prevalent in 1750, so as to hold 21st-century global warming since then to 2 K, implying λ_{tra} = 0.4 K W^{-1} m^{2}. This lesser rate, more suited to sub-centennial-scale appraisals than the bicentennial-scale 0.5 K W^{-1} m^{2}, will be adopted here, though other values may readily be substituted.

To reflect the IPCC’s wide error-intervals, where λ_c is a central bicentennial-scale climate-sensitivity estimate λ will fall on the 1 σ interval $[0.8\lambda_c, 1.2\lambda_c]$ (from the ±0.69 K 1σ error-bar in IPCC, 2007, p. 798, box 10.2), or on the >66%-probability interval $[0.6\lambda_c, 1.4\lambda_c]$ (derived *ibid.*, p. 12). So, where $\lambda_c = 0.5$ K W^{-1} m^2, λ will fall on [0.4, 0.6] to 1 σ, and on [0.3, 0.7] with probability >0.66.

Recall that IPCC (IPCC, 2001, p. 358, Table 6.2), following Myhre *et al.* (1998), takes the CO2 forcing in W m^{-2} as 5.35 times the logarithm of a given proportionate change C_b/C_a in CO2 concentration, where C_a is the unperturbed value. Note that there was no statistically-significant warming from 1997-2012 (RSS, 2012; UAH, 2012). Then projected CO2 concentration C_{2100} in 2100, as the six-scenario mean, is 700 ppmv against 391 ppmv in 2011 (Conway & Tans, 2011), implying CO2-driven warming from 2011-2100 of $\lambda_{\mathrm{tra}}[5.35 \ln(C_{2100}/C_{2011})] = 0.4[5.35 \ln(700/391)] = 1.25$ K, similar to the 1.5 K established earlier from IPCC (2007, Table SPM.3).

Observed warming since 1950 has occurred at a rate equivalent to 1.2 K/century (HadCruT3, 2012). Of this, 70%, or 0.8 K/century, is attributable to CO2; and, since IPCC (2007) finds that up to half of the warming since 1950 might be natural, the centennial rate of CO2-driven warming could have been as low as 0.4 K/century. The IPCC’s implicit 1.5 K/century for the 21st century may accordingly be best seen as an upper bound rather than as a central estimate.

Table 2 summarizes official projections & observations of 21st-century warming:

Projected anthopogenic warming, 2000-2100	Source	ΔT_{C21}
High-end projection	Stern (2006)	10-11K
Central projection	Stern (2006)	5-6 K
Low-end projection	Stern (2006)	2-3 K
Mean projection: all anthropogenic warming	IPCC (2007)	2.8 K
… of which, warming not already committed	IPCC (2007)	2.2 K
… of which, fraction caused by CO2 emissions	” ” Tbl. SPM.3	1.5 K
” ” ” ” by calculation	(*v.* text *supra*)	1.25 K
Observed warming rate/century, 1950-2011	HadCRUt3	1.2 K
” ” ” ” (from CO2 only)	0.7 ΔT	0.8 K
(from CO2 if half of warming was manmade)	0.7 ΔT / 2	0.4 K

Method

In this deliberately very simple method, only two case-specific inputs are required: C_y, the projected business-as-usual CO2 concentration in the target final year y of the policy, and p, the proportion of projected global business-as-usual CO2 emissions till year y that the policy is intended to abate.

Eq. (1) determines C_{pol}, the CO2 concentration in parts per million by volume (somewhat below C_y) in year y that may be achievable by following a given policy to mitigate the radiative forcing from atmospheric CO2 enrichment from 2010 (when $C_{2010} = 390$ ppmv) till year y. Eq. (1) also determines ΔT_{nix}, the quantum (in K) of transient global warming that the policy will abate if pursued until year y. Eq. (1) may be tuned to represent any forcing (see Table 4 below): but only warming attributable to the CO2 forcing is demonstrated here.

$$\begin{aligned}\Delta T_{\text{nix}} &= \lambda_{\text{tra}}\, \Delta F_{\text{nix}} \\ &= 0.4 \left[5.35 \ln\left(\frac{C_y}{C_{\text{pol}}}\right)\right] \\ &= 2.14 \ln\left(\frac{C_y}{C_y - p(C_y - 390)}\right). \qquad (1)\end{aligned}$$

Mitigation cost-effectiveness is here defined as the cost of abating 1 K CO2-driven global warming on the assumption that all measures to mitigate all CO2-driven warming to year y are as cost-effective as the policy under consideration. On the same assumption, the policy's *global abatement cost* is defined as the total cost from 2010 to year y (as a global cash cost, or a per-capita cost, or a percentage of real global GDP) of abating all anthropogenic warming that the IPCC projects will occur by year y (i.e. over the policy term) without mitigation.

Eq. (2) gives the mitigation cost-effectiveness M in US dollars per Kelvin of global warming abated. The lesser the value of M, the more cost-effective is the policy, enabling policymakers rapidly reliably to compare the estimated mitigation cost-effectiveness of competing mitigation proposals.

$$M = \frac{x}{\Delta T_{\text{nix}}}. \qquad (2)$$

Global abatement cost: Where $w = 7 \times 10^9$ is world population, q is the fraction of total anthropogenic forcing attributable to CO2, and $\Delta T_y = 2.14 \ln(C_y / C_{2010}) / q$ is the projected anthropogenic global warming to year y, Eqs. (3-5) give the policy's global abatement cost over the term to year y in cash; per head of global population; and as a percentage of real global 21st-century GDP r over the term:

Cash	Per capita	As % global GDP
$G = M\,\Delta T_y$	$H = G / w$	$J = 100G / r$
(3)	(4)	(5)

Derivation of Equation (1)

Where λ is a climate-sensitivity parameter in K W^{-1} m^2, consequent global warming in K may be expressed generally by Eq. (6):

$$\Delta T = \lambda\,\Delta F = \lambda\,[5.35 \ln(C_b/C_a)]. \tag{6}$$

As a check, taking λ_{tra} = 0.4 K W^{-1} m^2 for 1900-2100, at CO2 doubling Eq. (6) gives 0.4[5.35 ln(2)] ≈ 1.5 K, on the model-derived transient-climate-response interval [1, 3] K (IPCC, 2007, p. 749).

Where p, on [0, 1], is the fraction of future global emissions that a given CO2-reduction policy is projected to abate by a target calendar year y, and C_y is the IPCC's projected unmitigated CO2 concentration in year y, Eq. (7) gives C_{pol}, the somewhat lesser concentration in ppmv that may be expected to obtain in year y if the policy is followed:

$$C_{pol} = C_y - p(C_y - 390). \tag{7}$$

Table 3 gives central estimates of projected decadal values of C_y for 2010-2100.

y	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
C_y	390	410	440	480	510	550	590	630	660	700

Table 3. Business-as-usual CO2 concentrations, 2010-2100, as the mean of the central projections for all emissions scenarios (IPCC, 2007, p. 803, Fig. 10.26).

Eq. (8), of similar form to Eq. (6), determines how much warming ΔT_{nix}, in Kelvin, a specific policy intended to cut CO2 emissions will abate in the 21st century:

$$\begin{aligned}\Delta T_{nix} &= \lambda_{tra}\,[5.35 \ln(C_y/C_{2010}) - 5.35 \ln(C_{pol}/C_{2010})] \\ &= \lambda_{tra}\,[5.35 \ln\,(C_y/C_{pol})]. \end{aligned} \tag{8}$$

The second expressions of Eq. (8) and Eq. (1) are equivalent.

Other greenhouse gases

The method sketched here may be adapted to determine the mitigation cost-effectiveness and global abatement costs of greenhouse gases other than CO2. Table 4 summarizes some climate-relevant radiative forcing functions.

Trace gas	Radiative forcing ΔF g_y= business-as-usual; g_{pol} = lesser conc. after policy	Concentration in 2010
CH4	$0.036(\mu_y^{0.5} - \mu_{\mathrm{pol}}^{0.5}) + f(\mu_{\mathrm{pol}}, \nu_{\mathrm{pol}})^{\dagger} - f(\mu_y, \nu_{\mathrm{pol}})^{\dagger}$	1816 ppbv
N2O	$0.12(\nu_y^{0.5} - \nu_{\mathrm{pol}}^{0.5}) + f(\mu_{\mathrm{pol}}, \nu_{\mathrm{pol}})^{\dagger} - f(\mu_{\mathrm{pol}}, \nu_y)^{\dagger}$	324 ppbv
CFC11	$0.00025(\beta_y - \beta_{\mathrm{pol}})$	238 pptv
CFC12	$0.00033(\gamma_y - \gamma_{\mathrm{pol}})$	532 pptv
SF6	$5.2^{-4}(\varphi_y - \varphi_{\mathrm{pol}})$	7.31 pptv
SO2	$-[0.03\, \psi_y/\psi_{\mathrm{pol}} + 0.08 \ln(1+\psi_y/34.4)/(1+\psi_{\mathrm{pol}}/34.4)]$	Unknown

† $f(\sigma,\tau) = 0.47 \ln[1 + 2.01 \text{ x } 10^{-5}(\sigma\tau)^{0.75} + 5.31 \text{ x } 10^{-15}\, \sigma(\sigma\tau)^{1.52}]$

Table 4. Forcing functions for methane (CH4), nitrous oxide (N2O), the chlorofluorocarbons CFC11, CFC12, sulfur hexafluoride (SF6), and sulfur dioxide (SO2). Global concentrations for SO2 are unknown because its concentration is highly variable both spatially and temporally. Source: IPCC (2007).

The inter-temporal discount rate

By how much should future costs and benefits be discounted to net present value to take account of the uncertainties inherent in any long-term investment appraisal such as that of a given policy's effect in reducing global warming?

Stern (2006) adopts a discount rate not exceeding 1.4% (it may in practice have been as low as 0.1%: Stern Review team, pers. comm., 2006), well below HM Treasury's standard 3.5% "Green Book" rate, which is in turn somewhat below the 5% rate typical in the literature (e.g. Nordhaus, 2008; Murphy, 2008).

Stern justifies his rate as follows: "The most straightforward and defensible interpretation (as argued in the Review) of [the utility discount factor] δ is the probability of existence of the world. In the Review, we took as our base case δ = 0.1%/year, which gives roughly a one-in-ten chance of the planet not seeing out this century. … [Per-capita consumption growth] *g* is on average ~1.3% in a world without climate change, giving an average consumption or social discount rate across the entire period of 1.4% (being lower where the impacts of climate change depress consumption growth)" (Dietz *et al.,* 2007).

HM Treasury has moved in Stern's direction by adopting two reduced "climate-change" discount rates that are initially commercial and are reduced after year 30 and again after year 75 to allow for "very-long-term, substantial, and for practical purposes irreversible wealth transfers between generations" (Grice, 2011; Lowe, 2008).

Over a century these variable rates are equivalent to uniform rates of 3.22% and 2.75% respectively – closer to the Treasury's standard 3.5% "Green Book" discount rate than to Stern's 1.4% or the 1.35-2.65% in Garnaut (2008).

Klaus (2011) recommends a market approach: "To make a rational choice means to pay attention to inter-temporal relationships and to look at the opportunity costs. It is evident that … assuming a very low (near-zero) discount rate … neglect[s] the issue of time and of alternative opportunities. Using a low discount rate in global-warming models means harming current generations vis-à-vis future generations. Undermining current economic development also harms future generations."

Klaus continues: "Economists representing very different schools of thought, from Nordhaus (2008) to Murphy (2008), tell us convincingly that the discount rate – indispensable for any inter-temporal calculations – should be around the market rate of 5%, and that it should be close to the real rate of return on capital, because only that rate represents the opportunity cost of climate mitigation."

Accordingly, a 5% discount rate will be adopted in the illustrative case studies that follow, though other rates will be considered later.

Since warming is not occurring at the rate the IPCC predicts, the extreme warming rates of 5-6 K or even 10-11 K in Stern (2006) are not modeled here, though the method allows for them if required.

It will be assumed that the IPCC's central estimate of 2.8 K anthropogenic warming will occur by 2100, and that the welfare loss arising from climate inaction will be 1.5% of GDP, on Stern's [0, 3] %-of-GDP interval.

Welfare loss from inaction

Table 5 adjusts the projected 21st-century 1.5%, 3%, 5% and 20% global costs of inaction given in Stern (2006), in line with the published discount rates shown:

Stern (2006) inaction costs adjusted for discount rate	Dsct. Rate	yr 0 -30	yr 31 -75	yr 76 -100	Cost: % of GDP	Cost: % of GDP	Cost: % of GDP	Cost: % of GDP
Units	%	%	%	%	GDP	GDP	GDP	GDP
Stern (2006)	*1.40*				*1.50%*	*3.0%*	*5.0%*	*20%*
Garnaut (2011) high	2.65				0.72%	1.5%	2.4%	9.7%
HM Tsy low (Lowe, 2008)	2.75	3.00	2.57	2.14	0.69%	1.4%	2.3%	9.2%
HM Tsy high (Grice, 2011)	3.22	3.50	3.00	2.50	0.54%	1.1%	1.8%	7.3%
HM Tsy Green Book rate	3.50				0.48%	1.0%	1.6%	6.4%
Market rate (s, 2011)	5.00				0.26%	0.5%	0.9%	3.5%

Table 5. Estimates of the welfare loss over 100 years owing to climate inaction at the discount rates shown are determined by multiplying Stern's 1.5%-, 3%-, 5%- and 20%-of-GDP estimated 21st-century inaction costs by the ratio of 21st-century GDP discounted at Stern's 1.4% rate to 21st-century GDP discounted at the mean rates shown. Annual GDP growth in the 21st century is assumed uniform at 3% throughout the table.

Adjustments between a given inaction cost Z_s mentioned by Stern on the basis of a 1.4% discount rate d_s and the equivalent inaction cost Z_m on the basis of a 5% market rate d_m may be conveniently made using (9), where t is the term of the policy in years; a is each successive year from 1 to t; g is an assumed uniform annual percentage growth rate (here, 3%); d_m is the preferred discount rate (here, the 5% minimum market rate); d_s is the discount rate at which the inaction cost was determined (here, Stern's 1.4%); $|n|$ is the absolute value of n; and $\operatorname{sgn}(n)$ is the signum function.

$$Z_m = Z_s \frac{\sum_{a=1}^{t} \left(1 + \frac{|g - d_m|}{100}\right)^{a \operatorname{sgn}(g - d_m)}}{\sum_{a=1}^{t} \left(1 + \frac{|g - d_s|}{100}\right)^{a \operatorname{sgn}(g - d_s)}} \qquad (9)$$

Some published estimates of the welfare loss from failing to take action to mitigate global warming by reducing future emissions of CO2 follow. The reviewed literature, summarized by Tol (2009ab), suggests that the global inaction cost will be 1-5% of GDP:

1.0 K warming will cost 2.5% of GDP (Tol, 2002). 2.5 K warming will cost 0.9% (Nordhaus, 2006), 1.4% (Fankhauser, 1995), 1.5% (Nordhaus & Boyer, 2000), 1.7% (Nordhaus & Yang, 1996), 1.9% (Tol, 1995), 2.5% (Plamberk & Hope, 1996), or 0.0-0.1% of GDP (from market impacts only: Mendelsohn *et al.,* 2000). 3 K warming will cost 1.3-4.8% of GDP (Nordhaus, 1994ab).

The cost/benefit ratio

Since this much-simplified model excludes all costs and benefits external to those of CO2 mitigation, the ratio of the global abatement cost J (Eq. 5) of climate action, expressed as a percentage of GDP over the term of the policy, to the market GDP cost Z_m of the climate-related damage that is projected to arise from inaction is, for present purposes, the policy's cost/benefit ratio.

Nordhaus (2012) argues that the absolute difference between cost and benefit, rather than the ratio, should determine CO2 mitigation policies:

"Suppose we were thinking about two policies. Policy A has a small investment in abatement of CO2 emissions. It costs relatively little (say $1 billion) but has substantial benefits (say $10 billion), for a net benefit of $9 billion. Now compare this with a very effective and larger investment, Policy B. This second investment costs more (say $10 billion) but has substantial benefits (say $50 billion), for a net benefit of $40 billion. B is preferable because it has higher net benefits ($40 billion for B as compared with $9 for A), but A has a higher benefit-cost ratio (a ratio of 10 for A as compared with 5 for B). This example shows why we should, in designing the most effective policies, look at benefits minus costs, not benefits divided by costs."

However, the true choice is not between a small but cost-effective investment and a larger though less cost-effective investment that will yield a greater absolute benefit. A rational choice surely depends upon appraising the cost of acting to prevent global warming by way of a given CO2 mitigation policy compared with the cost of the climate-related damage that might arise from inaction over the term of the policy.

In the latter context, the estimated cost of inaction is fixed, but various policy options for action to mitigate CO2 emissions are available, wherefore the cost/benefit ratio is of no less relevance than the absolute cost or benefit of action against inaction.

Illustrative case studies

In the brief illustrative case studies that follow, uniform real GDP growth of 3%/year from $60 tr/year in 2010 (World Bank, 2011) is assumed in all cases, with a further 2% cost escalator for the Australian emissions-trading scheme.

Since the 5% discount rate prevalent in the literature rather than Stern's 1.4% is adopted here, Stern's estimated welfare loss of 1.5-20% of GDP arising in the absence of any mitigation falls to 0.26-3.5% of GDP (Table 5). Since there is no sign of warming above the IPCC's central estimate, the least inaction cost, 1.5% of GDP discounted over the term, is the basis for comparison with the discounted costs of action to establish the cost/benefit ratio in each case study.

Case study 1: US carbon-trading Bill

At \$180 bn/year for 40 years, total \$7.2 tr, discounted to \$5 tr at p.v., the climate Bill (HR 2454, 2009, s. 311) would have abated 83% of US CO2 emissions by 2050. The US emits 17% of global CO2 (derived from Olivier & Peters, 2010, table A1). Thus p = 0.1411. From Table 1, business-as-usual CO2 concentration in 2050 would be 510 ppmv, falling to 493.1 ppmv (from Eq. 7) via the Bill. From Eq. (1), forcing abated is 0.2 W m^{-2} and warming abated is 0.07 K; from Eq. (2), mitigation cost-effectiveness is \$69 tr/K; from Eq. (3), the global abatement cost of all projected warming to 2050 is \$56 tr, or (from Eq. 4), \$8,000 per capita of global population, or (from Eq. 5), 3.4% of global GDP to 2050. The mitigation cost exceeds fivefold the benefit in preventing climate damage.

Case study 2: UK Climate Change Act

At an officially-estimated cost of \$1.2 tr by 2050, discounted to \$835 bn, the Climate Change Act (2008, s. 1(1)), aims to cut 80% of UK emissions, which are 1.5% of world emissions (derived from Olivier & Peters, 2010, table A1). Thus p = 0.012. Business-as-usual CO_2 concentration of 510 ppmv in 2050 would fall to 508.6 ppmv via the Climate Change Act. Forcing abated is 0.015 W m^{-2}; warming abated is 0.006 K; mitigation cost-effectiveness is \$138 tr/K; and global abatement cost to 2020 is \$113 tr, or \$16,000/head, or 6.8% of global GDP to 2050. Cost exceeds benefit 9-fold.

Case study 3: EU carbon trading

EU carbon trading costs \$92 bn/year (World Bank, 2009, p. 1), here multiplied by 2.5 (implicit in Lomborg, 2007) to allow for non-trading mitigation measures. Total cost is \$2 tr at p.v. by 2020. The EU aims to halt 20% of its emissions, which are 13% of global emissions (from Boden *et al.,* 2010ab). Thus p = 0.026. Business-as-usual CO_2 concentration of 410 ppmv in 2020 would fall to 409.5 ppmv via the policy. Forcing abated is 0.007 W m^{-2}; warming abated is 0.003 K; mitigation cost-effectiveness is \$763 tr/K; and the global abatement cost of \$117 tr is \$17,000 per capita, or 21.5% of GDP to 2020. Mitigation costs 17.5 times the cost of climate-related damage in the absence of mitigation.

Case study 4: Californian cap and trade

Under the cap and trade Act (AB 32 of 2006), which took full effect in August 2012, some \$182 billion per year (Varshney & Tootelian, 2009) will be spent for a decade on cap and trade and related measures. The report has been criticized for overstating costs: accordingly, one-quarter of this value will be taken over a ten-year term, giving a discounted cost of \$410 billion, to abate 25% of current emissions, which represent 8% of US emissions, which represent 18.7% of global emissions (derived from Olivier & Peters, 2010, table A1). Thus p = 0.0033. CO_2 concentration would fall from a business-as-usual 410 to 409.93 ppmv by 2020. Forcing abated is 0.001 W m^{-2}; warming abated is 0.00034 K; mitigation cost-effectiveness is \$1200 tr/K; global abatement cost is \$183 tr, or \$26,000/head, or 34% of global GDP to 2020. Action costs 28 times inaction.

Case study 5: Thanet Wind Array

Subsidy to the world's largest wind-farm, off the English coast, guaranteed at \$100 mn annually for its 20-year life, is \$1.6 bn at p.v. Rated output of the 100 turbines is 300 MW, but wind-farms yield only 24% of rated capacity (Young, 2011, p. 1), so total output, at 72 MW, is 1/600 of mean 43.2 GW UK electricity demand (Department for Energy and Climate Change, 2011). Electricity is 33% of UK CO_2 emissions, which are 1.5% of global emissions, so $p = 8.333 \times 10^{-6}$. Business-as-usual CO_2 concentration in 2030 would be 440 ppmv, falling to 439.9996 ppmv as a result of the subsidy. Forcing abated is 0.000005 W m^{-2}; warming abated is 0.000002 K; mitigation cost-effectiveness is \$800 tr/K; and the global abatement cost of almost \$300 tr is \$42,000/head, or 30% of GDP to 2030. Action costs 29 times inaction.

Case study 6: Australia cuts emissions 5% in 10 years

Carbon trading in Australia, as enacted the Clean Energy legislation (Parliament of the Commonwealth of Australia, 2011), costs \$10.1 bn/year, plus \$1.6 bn/year for administration (Wong, 2010, p. 5), plus \$1.2 bn/year for renewables and other costs, a total of \$13 bn/year, rising at 5%/year, or \$130 bn by 2020 at n.p.v., to abate 5% of current emissions, which represent 1.2% of world emissions (derived from Boden *et al.,* 2010ab). Thus $p = 0.0006$. CO_2 concentration would fall from a business-as-usual 412 to 411.987 ppmv after ten years. Forcing abated is 0.0002 W m^{-2}; warming abated is 0.00006 K; mitigation cost-effectiveness is $2,000 tr/K; global abatement cost of projected warming to 2020 is $300 trillion, or $45,000/head, or 59% of global GDP to 2020. Action costs 48 times inaction.

Case study 7: Oldbury Primary School wind turbine

On 31 March 2010 Sandwell Council, England, answered a freedom-of-information request, disclosing that it had spent $9694 (£5875) on buying and installing a small wind-turbine like one at a primary school in Oldbury which had in a year generated 209 KWh – enough to power a single 100 W reading-lamp for <3 months. Assuming no maintenance costs, and discounting revenues of $0.18 (11p)/KWh for 20 years to p.v. of $623, net project cost is $9070. p = 209 KWh / 365 days / 24 hrs / 43.2 GW x 0.33 x 0.015 = 2.76×10^{-12}. CO2 concentration of 440 ppmv will fall to 439.9999999999 ppmv. Forcing abated is 0.000000000002 W m^{-2}; warming abated is 0.000000000001 K; mitigation cost-effectiveness is $13,500 tr/K; and the global abatement cost, at close to $5,000 tr, is $700,000/head, or 500% of global GDP to 2030. Action costs almost 500 times inaction.

Case study 8: London bicycle-hire scheme

In 2010 the Mayor of London set up what he called a “Rolls-Royce” scheme at US$ 130 mn for 5000 bicycles (>$26,000 per bicycle). Transport represents 15.2% of UK emissions (from Office for National Statistics, 2010, table C). Cycling represents 3.1 bn of the 316.3 bn vehicle miles travelled on UK roads annually (Department for Transport, 2011). There are 23 mn bicycles in use in Britain (Cyclists’ Touring Club, 2011). Global emissions will be cut by 1.5% of 15.2% of 3.1/316.3 times 5000/23 mn. Thus $p = 4.886 \times 10^{-9}$. If the lifetime of bicycles and docking stations is 20 years, business-as-usual CO2 concentration of 440 ppmv will fall to 439.9999998 ppmv through the scheme. Forcing abated is 0.000000003 W m^{-2}; warming abated is 0.000000001 K; mitigation cost-effectiveness exceeds $110,000 tr/K; and the global abatement cost of $40,000 tr is $5.8 mn per capita, or 4000% of global GDP to 2030. Action costs almost 4000 times inaction.

Results

Government estimates of abatement cost (cases 1-2) are of the same order as those in Stern (2006), Garnaut (2008) and the reviewed literature. However, the costs of specific measures prove considerably higher than all such estimates, which have proven optimistic. Gesture policies (cases 7-8) are particularly cost-ineffective. However, this analysis is strictly confined to comparing the costs of taking climate action now with those of climate-related damage that might arise if no action were taken, excluding all other costs and benefits. In particular, benefits from investment in alternative or renewable energy are excluded, since they are likely to be comfortably exceeded by the opportunity losses arising from the diversion of substantial resources from the productive sector in the form of mitigation costs. Opportunity losses are also excluded from the accounting.

This analysis is not a complete study of all the costs and benefits of attempted climate mitigation. Its focus is on enabling policy-makers to understand the relationship between the IPCC's implicit central estimates of sub-centennial-scale transient climate sensitivity and of the forcing and warming likely to be forestalled by a given mitigation policy, allowing a first approximation of how much (or how little) global warming that policy may forestall. The new climatological equations derived here can readily be adapted for detailed cost-benefit analyses and comparisons beyond the scope of the present paper.

Table 6 summarizes the results of the case studies:

Table 6 Case study [#]	Warming abated (K by year y)	Mitigation cost-effect. ($ tr/K)	Abate. cost (%GDP)	Action/ inaction ratio
[1] US cap-&-trade	0.07 K by 2050	$69 tr/K	3.4%	5 x
[2] UK Climate Act	0.006 K by 2050	$138 tr/K	6.8%	9 x
[3] EU carbon trading	0.003 K by 2020	$763 tr/K	22%	18 x
[4] California AB 32	0.0+ K by 2020	1,155 tr/K	33%	26 x
[5] Thanet Wind Array	0.0+ K by 2030	$803 tr/K	30%	29 x
[6] Australia 5% cut	0.0+ K by 2020	$2082 tr/K	59%	48 x
[7] School windmill	0.0+ K by 2030	$13,500 tr/K	504%	488 x
[8] London cycle hire	0.0+ K by 2030	$109,000 tr/K	4090%	3956 x

Table 6. Summary of case-study results, assuming a 5% intertemporal discount rate,uniform 3% annual GDP growth, and a 1.5%-of-GDP inaction cost.

In Table 7, the effect of various inter-temporal discount rates is illustrated by comparing the mitigation and inaction costs of the Australian Government's carbon dioxide tax policy (case study 5) after applying Stern's and Garnaut's rates, as well as the Treasury's standard 3.5% flat rate and the 5% minimum market rate. Over longer periods than a decade, differing discount rates have a greater impact.

Table 7	Stern	Garnaut 2	GreenBook	Market
Discount rate	1.4%	2.65%	3.5%	5.0%
Case study 5: cost *x*	\$159 bn	\$148 bn	\$141 bn	\$130 bn
Mitigat. cost-effect.	\$2.8 qd/K	\$2.6 qd/K	\$2.5 qd/K	\$2.2 qd/K
Global abatemt. cost	\$378 tr	\$352 tr	\$336 tr	\$310 tr
” ” per capita	\$54,000	\$50,000	\$48,000	\$44,000
” ” as % GDP	58%	58%	58%	58%
Global inaction cost	1.5-20%	1.4-18.6%	1.3-17.8%	1.2-16.4%
Action/inaction ratio	2.9-38	3.1-41	3.2-42	3.5-48

Table 7. The policy cost *x* of case study 6*;* the mitigation cost-effectiveness *M*; the per-capita global abatement cost *J*; the cash global abatement cost *H* in cash and as a percentage of GDP; the upper and lower bounds of the global welfare loss interval *I* arising from inaction, expressed as percentages of GDP; and the climate action/inaction ratio of *H* (expressed as a percentage of GDP) to the bounds of *I*. N.B.: mn = million; bn = billion; tr = trillion; qd = quadrillion.

Even the use of Stern's minimalist discount rate shows that the global abatement cost of the carbon tax – i.e., the cost of abating all global warming over the decade to 2020 if all measures to mitigate global warming from all anthropogenic causes were as cost-effective as the Australian Government's proposal – will greatly exceed even Stern's maximum 20% cost of climate-related damage arising from worldwide inaction.

Discussion

For the sake of simplicity and accessibility, the focus of the method is deliberately narrow. Potential benefits external to CO2 mitigation, changes in global-warming potentials, variability in the global-GDP growth rate, or relatively higher mitigation costs in regions with lower emission intensities are ignored, for little error arises. GDP growth rates and climate-inaction costs are assumed as uniform, though in practice little climate-related damage would arise unless global temperature rose by at least 2 C° above today's temperatures.

Given the small quanta of warming abated by CO2-reduction policies, as well as the breadth of the intervals of published estimates of inaction and mitigation costs, the greater complexity of adopting non-uniform GDP growth rates and climate-inaction costs may in any event be otiose.

The case studies suggest official projections may be optimistic against the cost-effectiveness of specific policies. Based on the US and UK Governments' estimates, the global abatement cost of their policies would be 5 and 9 times the cost of inaction respectively: however, the global abatement costs of the EU's carbon trading scheme and the taxpayer subsidy to the world's largest wind farm would 18 and 29 times inaction respectively, with smaller schemes proving considerably less cost-effective still. In general, smaller projects seem less cost-effective than larger projects: but projects of any scale are cost-ineffective.

A substantial reduction in global CO2 emissions, maintained over centuries, might offset some of the warming caused by the pre-existing increase in atmospheric CO2 concentration from 278 ppmv in 1750 to 390 ppmv in 2010.

After a sufficiently long period of global emissions reduction ($y \gg 2100$), it may become justifiable to reduce the value 390 in the denominator of Eq. (1) stepwise towards the pre-industrial CO2 concentration 278 ppmv, increasing ΔT_{nix} and consequently improving cost-effectiveness by reducing M. However, within the 21st century even the immediate and total elimination of CO2 emissions would only abate ~1.5 K global warming.

For numerous reasons, Eq. (1) and the case studies tend to overstate the warming that any CO2-reduction policy may abate, and also to overstate cost-effectiveness. The IPCC takes CO2's mean atmospheric residence time as 50-200 years: if so, little mitigation will occur within the 21st century. It is here assumed that any policy-driven reduction in CO2 concentration occurs at once, when it would be likely to occur stepwise to year y, halving the warming otherwise abated by that year and doubling the cost-ineffectiveness.

In some cases, it is assumed that the policy will meet the emissions-reduction target on its own, ignoring the often heavy cost of all other mitigation measures intended to contribute to achievement of the target. In most case studies capital costs only are counted and running costs excluded. Capital costs external but essential to a project, such as provision of spinning-reserve generation for wind turbines on windless days, are excluded. Emissions from project construction and installation, such as concrete bases for wind turbines, are ignored, as are costs and CO2 emissions arising from necessary external operating expenditures such as spinning-reserve for wind turbines.

If the IPCC's central projections exaggerate the warming that may arise from a given increase in atmospheric CO2 concentration, the warming abated may be less than shown. Though emissions are rising in accordance with the IPCC's A2 emissions scenario, concentration growth has been near-linear for a decade, so that outturn by 2100 may be considerably below the IPCC's mean estimate of 700 ppmv.

The climate-sensitivity parameter λ_{tra} used in the case studies is centennial-scale: accordingly, over the shorter periods covered by the studies a somewhat lesser coefficient (allowing for the fact that longer-term temperature feedbacks may not yet have acted) and consequently less warming abated would reduce mitigation cost-effectiveness.

Finally, all opportunity losses from diverting resources to global-warming mitigation are ignored.

Conclusions

The case studies indicate that governments' initial abatement-cost estimates have proven optimistic. It is unlikely that any policy to abate global warming by taxing, trading, regulating, reducing, or replacing greenhouse-gas emissions will prove cost-effective solely on grounds of the welfare benefit foreseeable from global-warming mitigation alone.

High abatement costs, and the negligible returns in warming abated, imply that focused adaptation to the consequences of such future warming as may occur may be considerably more cost-effective than any attempted mitigation. Mitigation policies inexpensive enough to be affordable are likely to prove ineffective, while policies costly enough to be effective will be unaffordable. Since the opportunity cost of mitigation is heavy, the question arises whether mitigation should be attempted at all.

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