Is CO2 mitigation cost-effective?

Christopher Monckton of Brenchley
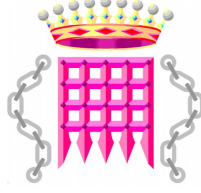monckton@mail.com

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Introduction

Hitherto, the economic literature has chiefly addressed the cost-effectiveness of climate mitigation globally. A simple yet comprehensive metric, derived from methods of the Intergovernmental Panel on Climate Change (IPCC, here taken as reliable), is intended to enable even non-specialist policy-makers to determine not only how much global warming any proposed CO2-reduction policy may be expected to forestall but also the policy's mitigation cost-effectiveness and the abatement cost of forestalling a given quantum of future warming, on the assumption that the global cost-effectiveness of all mitigation strategies is equivalent to that of the policy.

Brief case studies illustrate how cost-benefit may be addressed by comparing the mitigation cost-effectiveness of competing CO2-reduction policies with one another, and by comparing their abatement costs with published estimates of the welfare loss arising from unmitigated climate change. As benchmarks, Stern (2006, p. vi), using the 0.1% discount rate that will be adopted here for illustration, estimates that 1% of 21st-century global GDP will suffice to forestall a projected 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) puts Australia's 21st-century mitigation and inaction costs at 3.2-4% and 6% respectively, against a projected 5.1 K unmitigated global warming to 2100. The economic literature puts the inaction cost at 1-4%.

Costs external to the policy itself and benefits external to mitigation of CO2 forcing are beyond the focus of this paper, but the metric may readily be adapted to encompass them.

Method

For simplicity, central estimates from IPCC's A2 emissions scenario are used throughout. Eq. (1) determines C_{pol}, the atmospheric CO2 concentration in ppmv (somewhat below IPCC's projected A2 business-as-usual concentration C_y) achievable by following any proposed policy to mitigate the radiative forcing from atmospheric CO2 enrichment from 2010 (when C_{2010} = 390 ppmv) till a target calendar year y. Eq. (1) also determines ΔT_{nix}, the quantum (in K) of transient global warming that the policy will be likely to forestall if pursued until year y. Only two case-specific inputs are required: C_y itself, and p, the proportion of projected global business-as-usual CO2 emissions till year y that the policy is intended to forestall. A non-case-specific input is the climate-sensitivity parameter λ, defined later, which may be set to encompass the interval of IPCC global-warming projections under all emissions scenarios. Eq. (1) may be tuned to represent any forcing (see Table 2 below): but only warming attributable to the CO2 forcing is demonstrated here.

$$\Delta T_{nix} = \lambda \, \Delta F$$
$$= \lambda \left[5.35 \ln \left(\frac{C_y}{C_{pol}} \right) \right]$$
$$= \lambda \left[5.35 \ln \left(\frac{C_y}{C_y - p(C_y - 390)} \right) \right]. \tag{1}$$

Mitigation cost-effectiveness is defined as the cost of forestalling 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 cost (expressed either as a percentage of real global GDP from 2010 to year y or as a cash cost per capita to year y) of forestalling all global warming from all forcings that the IPCC projects will occur by year y without mitigation.

Where ΔT_{allCO2} is all projected CO2-driven warming to year y, where x is the net present value of the policy's cost, and where x/p is the cost of mitigating all CO2-driven warming to year y, Eq. (2) gives the mitigation cost-effectiveness in US$ per Kelvin of global warming forestalled. The lesser the mitigation cost-effectiveness M, the more cost-effective is the policy, enabling policymakers reliably to compare competing mitigation proposals.
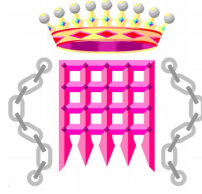
$$M = \left(\frac{x}{p} \right) \Delta T_{allCO2}^{-1} = \frac{x}{p\lambda \left[5.35 \ln(C_y/390) \right]}. \tag{2}$$

Where q is the fraction of total radiative forcing attributable to CO2, Eq. (3) gives the policy's abatement cost as a percentage of total real global 21st-century GDP r to year y:

$$H = \frac{100x}{pqr}. \tag{3}$$

Eq. (4) gives the per-capita abatement cost in US $/head assuming 7 bn world population:

$$J = \frac{x}{7 \times 10^9 pq}. \tag{4}$$

Derivation of Equation (1)

IPCC (2001), 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 atmospheric CO2 concentration, where C_a is the unperturbed value. Where λ is a climate-sensitivity parameter in K W⁻¹ m², consequent global warming in K may thus be expressed generally by Eq. (5):

$$\Delta T = \lambda\, \Delta F = \lambda\, [5.35\, \ln(C_b/C_a)]. \tag{5}$$

IPCC (2001, p. 354, citing Ramanathan, 1985) takes 0.5 K W⁻¹ m² as a typical value of λ. On the A2 emissions scenario, IPCC (2007, p. 13, table SPM.3) projects 3.4 K warming by 2100 in response to forcings from all sources summing to 8 W m⁻² (*ibid.,* p. 803, fig. 10.26), implying a 21ˢᵗ-century transient-sensitivity parameter λ_{tra} = 3.4 / 8 = 0.425 K W⁻¹ m², which the case studies will use. As a check, at CO2 doubling Eq. (5) gives 0.425[5.35 ln(2)] = 1.6 K, within the model-derived transient-climate-response interval [1, 3] K (*ibid.,* p. 749).

The parameter λ_{equ} for climate sensitivity when the climate has settled to equilibrium after our perturbation of it will exceed λ_{tra}. However, equilibrium is not reached for 1000-3000 years (Solomon *et al.,* 2009), so only 21ˢᵗ-century warming is policy-relevant: subsequent warming will occur too slowly to do unavoidable harm.

On the IPCC's A2 emissions scenario, CO2 concentration is projected to rise from 390 ppmv today (Tans, 2011) to 836 ppmv by 2100 (IPCC, 2007, ch. 10, p. 750). Accordingly, a central estimate of global warming preventable by 2100 even if all anthropogenic CO₂ emissions were to have ceased in 2010 is λ_{tra}[5.35 ln(836/390)] = 1.7 K.

To reflect the IPCC's wide error-intervals, where λ_c is a central estimate λ will fall on the 1 σ interval [0.8λ_c, 1.2λ_c] (from the ±0.69 K 1 σ error-bar in IPCC, 2007, p. 798, box 10.2), or on the >66%-probability interval [0.6λ_c, 1.4λ_c] (derived *ibid.,* p. 12). Thus, where λ_c = 0.425 K W⁻¹ m², λ will fall on [0.34, 0.51] to 1 σ, and on [0.26, 0.59] with probability >0.66.

Where *p*, on [0, 1], is the fraction of future global emissions that a given CO2-reduction policy is projected to forestall by a target calendar year *y,* and C_y is the IPCC's projected unmitigated CO2 concentration in year *y*, Eq. (6) gives C_{pol}, the somewhat lesser concentration in ppmv that may be expected to obtain in year *y* if the policy is followed:
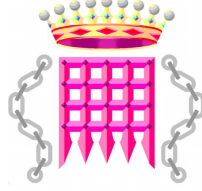
$$C_{pol} = C_y - p(C_y - 390). \tag{6}$$

Table 1 gives decadal values of C_y from 2010-2100 on the IPCC's A2 emissions scenario, whose central projection is that the anthropogenic fraction of CO2 concentration will grow exponentially from 390 ppmv in 2010 to C_{2100} = 836 ppmv by 2100.

y	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
C_y	390	412	438	469	506	551	604	668	744	836

Table 1. Business-as-usual CO2 concentrations, 2010-2100, on scenario A2 (IPCC, 2007). CO2 concentration in 2010 is 390 ppmv (Tans, 2011) compared with 280 ppmv in 1750, so that the anthropogenic component is 110 ppmv. Assuming all increases in CO2 concentration since 1750 are anthropogenic, in any calendar year *y* in the 90 years 2011-2100, IPCC's projected intra-decadal values of C_y on emissions scenario A2 are determined by the equation

$$C_y = 280 + 110 e^{\left(\frac{y-2010}{90}\ln\frac{C_{2100}-280}{110}\right)}.$$

Eq. (7), of similar form to the general Eq. (5), gives the quantum of warming ΔT_{nix}, in K, that a specific policy intended to cut CO2 emissions will forestall in the 21st century:

$$\Delta T_{nix} = \lambda_{tra} \left[5.35 \ln(C_y/C_{2010}) - 5.35 \ln(C_{pol}/C_{2010})\right]$$
$$= \lambda_{tra} \left[5.35 \ln (C_y/C_{pol})\right]. \tag{7}$$

The second expression of Eq. (7) is identical to the second expression of Eq. (1).

Other greenhouse gases

The metric described here may be adapted to determine the mitigation cost-effectiveness and global abatement costs of greenhouse gases other than CO2. Table 2 summarizes some climate-relevant radiative forcing functions:

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

$\dagger$ $f(\sigma,\tau) = 0.47 \ln[1 + 2.01 \times 10^{-5}(\sigma\tau)^{0.75} + 5.31 \times 10^{-15}\sigma(\sigma\tau)^{1.52}]$
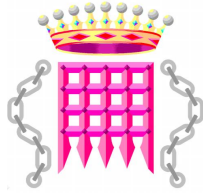
Table 2. Radiative forcing functions for methane (CH4), nitrous oxide (N2O), CFC11, CFC12, sulfur hexafluoride (SF6), and sulfur dioxide (SO2). Global values for SO2 are unknown because its concentration is highly variable both spatially and temporally: however, the forcing function is given so as to permit estimates to be used. Source: IPCC (2007).

Illustrative case studies

In the brief illustrative case studies that follow, A2-scenario 21st-century transient warming is taken as 3.4 K arising in response to a forcing of 8 W m^{-2}, so that the "near-invariant" (IPCC, 2001, ch. 6.1) transient-sensitivity parameter λ_{tra} is 3.4 / 8 = 0.425 K W^{-1} m^2. Real GDP growth of 3%/year from \$60 tr/year in 2010 (World Bank, 2011) is assumed in all cases. The 0.1% discount rate in Stern (2006) is applied, so that his estimated welfare loss of 5-20% of GDP arising in the absence of any mitigation may serve as a policy benchmark. The appropriateness of this rate is examined later. Some results are rounded.

Case study 1: US carbon-trading Bill

At \$180 bn/year for 40 years, total \$7.2 tr, discounted to \$7 tr at net present value, the climate Bill (HR 2454, 2009, s. 311) would have forestalled 83% of US CO$_2$ emissions by 2050. The US emits 17% of global CO$_2$ (derived from Olivier & Peters, 2010, table A1). Thus p = 0.1411. From Table 1, business-as-usual CO$_2$ concentration in 2050 would be 506 ppmv, falling to 489.632 ppmv (from Eq. 5) via the Bill. From Eq. (1), warming forestalled is 0.07 K; from Eq. (2), mitigation cost-effectiveness is \$84 tr/K; from Eq. (3), the global abatement cost of all projected warming to 2050 is almost \$100 tr, or more than 2% of global GDP to 2050, or (from Eq. 4), \$14,000 per capita of global population.

Case study 2: Australia cuts emissions 25% in 10 years

Carbon Trading will cost $11.5 bn/year, plus $2.5 bn/year for innovation (Garnaut, 2011), plus $1.6 bn/year for administration (Wong, 2010, p. 5), all rising at 4%/year above GDP growth, or $231 bn by 2020 at n.p.v., to forestall 25% of current emissions, which are 1.2% of world emissions (derived from Boden *et al.,* 2010ab). Thus p = 0.003. CO_2 concentration would fall from a business-as-usual 412 to 411.934 ppmv by 2020. Warming forestalled is <0.0004 K; mitigation cost-effectiveness is $634 tr/K; global abatement cost of projected warming to 2020 is $151 trillion, or 21.3% of global GDP to 2020, or $21,000 per capita.

Case study 3: UK Climate Change Act

The UK accounts for 1.5% of global CO_2 emissions (derived from Olivier & Peters, 2010, table A1). At an officially-estimated cost of $1.2 tr by 2050, the Climate Change Act (2008, s. 1(1)), will cut 80% of UK emissions, which are 1.5% of world emissions. Thus p = 0.012. Business-as-usual CO_2 concentration in 2050 is 506 ppmv, falling to 504.608 ppmv via the Act. Warming forestalled is 0.006 K; mitigation cost-effectiveness is $167 tr/K; and global abatement cost to 2020 is $193 tr, or 4% of global GDP to 2050, or $27,500 per capita.
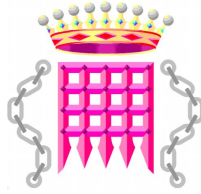
Case study 4: EU carbon trading

EU carbon trading costs $92 bn/year (World Bank, 2009, p. 1), or $915 bn at net present value 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 would be 412 ppmv by 2020, falling to 411.428 ppmv via the policy. Warming forestalled is 0.003 K; mitigation cost-effectiveness, excluding non-carbon-trading costs, is $282 tr/K; and the global abatement cost of $69 tr is 8% of GDP to 2020, or almost $10,000 per capita.

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 £1.96 bn at net present value. 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 x 10^{-6}. Business-as-usual CO_2 concentration in 2030 would be 438 ppmv, falling to 437.9996 ppmv as a result of the subsidy. Warming forestalled is 0.000002 K; mitigation cost-effectiveness is almost $900 tr/K; and the global abatement cost of $461 tr is 28% of GDP to 2030, or $66,000 per capita.

Case study 6: 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 (£11)/KWh for 20 years to net present value, net cost is $8943. p = 209 KWh / 365 days / 24 hrs / 43.2 GW x 0.33 x 0.015 = 2.76 x 10^{-12}. CO2 concentration of 438 ppmv will fall to 437.9999999999 ppmv. Warming forestalled is 0.0000000000007 K; mitigation cost-effectiveness is $12,000 tr/K; and the global abatement cost, at >$6000 tr, is 400% of global GDP to 2030, or $900,000 per capita.

Case study 7: 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 CO_2 concentration of 438 ppmv will fall to 437.9999998 ppmv through the scheme. Warming forestalled is 0.000000001 K; mitigation cost-effectiveness exceeds $100,000 tr/K; and the global abatement cost of $52,000 tr exceeds 3000% of global GDP to 2030, representing almost $7.5 mn per capita.

Results

Government estimates of abatement cost (cases 1-3) exceed by a factor 2-4 the 1% of GDP Stern considers achievable, but are similar to those in Garnaut (2008) and in the peer-reviewed literature. However, the costs of specific measures prove considerably higher than government estimates, which seem optimistic. The global abatement cost of measures equivalent to EU carbon trading, for instance, is almost 10% of global GDP, while that of policies equivalent to subsidizing the world's largest wind farm is 28% of GDP, substantially in excess of Stern's estimated maximum inaction cost.

Table 3 compares the results of the case studies with the estimates of 21st-century global abatement and inaction costs given in Stern (2006):

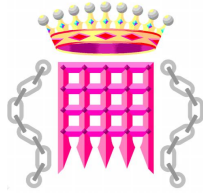| Case study [#]	Warming forestalled (K by year y)	Mitigation cost-effect. ($ tr/K)	Abate. cost (% GDP)	Cost/ capita ($000)
Stern 21st-century abate. cost	*3.4 K by 2100*	*$90 tr/K*	*1%*	*43*
[1] US cap-&-trade Bill	0.07 K by 2050	$84 tr/K	2%	14
[2] Australia 25% cut	0.0004 K by 2020	$634 tr/K	21.3%	21
[2] UK Climate Act	0.006 K by 2050	$167 tr/K	4%	27.6
Stern low-end inaction cost	*0.0 K by 2100*	*N.A.*	*5%*	*N.A.*
[4] EU carbon trading	0.003 K by 2020	$282 tr/K	9.7%	9.9
Stern high-end inaction cost	*0.0 K by 2100*	*N.A.*	*20%*	*N.A.*
[5] Thanet Wind Array	0.0+ K by 2030	$891 tr/K	28%	66
[6] Sandwell school windmill	0.0+ K by 2030	$12,270 tr/K	382%	907
[7] London bicycle hire scheme	0.0+ K by 2030	$101,000 tr/K	3142%	7450

Table 3. Results of the case studies, compared with estimates of global abatement and inaction costs (*italicized*) in Stern (2006).

Some estimates from the peer-reviewed economic journals are as follows, broadly suggesting that the global inaction cost will be 2-5% 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).

There are three main reasons for the differences between the peer-reviewed literature and the Stern report.

First, Stern adopts extreme a very high central estimate of the warming to be expected by 2100: 5 K compared with the IPCC's 3.4 K. The adoption by Stern of a central climate-sensitivity estimate half as much again as that of the IPCC provides a margin of caution, allowing its use as a starting point for determining global inaction costs on the basis of various other discount rates that occur in the literature.

Secondly, Stern adopts extreme estimates of various specific welfare losses (such as that from malaria, which will in fact be near-zero in response to global warming). Again, if we merely adopt his analysis *ad argumentum,* any analysis that we base upon it will err on the side of caution.

Thirdly, Stern adopts a 0.1% pure rate-of-time preference. The inter-temporal discount rate is, as we shall see, the prime determinant of variations between published cost-benefit estimates.

By how much, then, should future costs and benefits be discounted to net present value to take account of the uncertainties inherent in any long-term investment appraisal, and particularly inherent in an appraisal of the effect of a given policy on the future behavior of the non-linear, chaotic climate object?

Stern's 0.1% discount rate is based – according to a document linked from HM Treasury's website – on a misunderstanding by him of the literature on the economic treatment of inter-generational equity.

Certainly, Stern's near-zero rate is a long way below HM Treasury's standard 3.5% discount rate.

However, the Treasury moved in Stern's direction by adopting two reduced "climate-change" discount rates, that are initially commercial and are then 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 the entire 21st century these variable rates are equivalent to 3.22% and 2.75% respectively – much closer to the Treasury's standard 3.5% discount rate than to Stern's 0.1%.

Garnaut chooses two discount rates: 1.35% and 2.65%.

Finally, Dr. Vaclav Klaus, President of the Czech Republic, recommends a 5% discount rate to allow for uncertainties in climate prediction (Downing College climate conference, 2011).

In Table 4, all of these rates are modelled on a very simple basis. First 3% annual GDP growth throughout the 21st century is assumed.

Secondly, low-end and high-end estimates of the welfare loss owing to climate inaction are determined by multiplying Stern's 5%- and 20%-of-GDP estimated 21st-century inaction costs by the ratio of total 21st-century GDP discounted at Stern's 0.1% rate to total 21st-century GDP discounted at the mean discount rates shown:
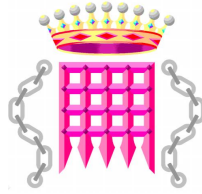
Table 4	Mean rate (%)	Yr 0 -30 (%)	Yr31 -75 (%)	Yr76 -100 (%)	Low est. of inaction cost	High est. of inaction cost
Stern (2006)	0.10				5.0% GDP	20% GDP
Garnaut (2011): #1	1.35				2.2% GDP	8.6% GDP
Garnaut (2011): #2	2.65				1.0% GDP	4.1% GDP
HM Tsy reduced (Lowe, 2008)	2.75	3.00	2.57	2.14	1.0% GDP	3.9% GDP
HM Tsy Green Book (Grice, 2011)	3.22	3.50	3.00	2.50	0.8% GDP	3.1% GDP
HM Treasury flat discount rate	3.50				0.7% GDP	2.7% GDP
President Klaus' discount rate	5.00				0.4% GDP	1.5% GDP

In Table 5, the effect of the interval of published discount rates is illustrated by comparing the mitigation and inaction costs of Dr. Garnaut's suggested carbon dioxide mitigation policy for Australia (case study 2) after applying Stern's and Garnaut's rates, as well as the Treasury's standard 3.5% flat rate and President Klaus' recommended 5% rate.

The table shows the policy cost x, the mitigation cost-effectiveness M, the per-capita global abatement cost J, the cash global abatement cost H, H expressed as a percentage of GDP, the global welfare loss interval I arising from inaction (with the upper and lower bounds of the interval expressed as percentages of GDP), and the ratio of H to the upper bound of I:
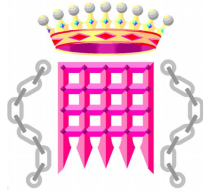
Table 5	Stern (2006)	Garnaut #1	Garnaut #2	Treasury	Klaus
Discount rate	0.1%	1.35%	2.65%	3.5%	5.0%
Policy cost x	$231 bn	$214 bn	$199 bn	$189 bn	$174 bn
Mitigat. cost-effect. M	$634 tr K^{-1}	$588 tr K^{-1}	$545 tr K^{-1}	$520 tr K^{-1}	$479 tr K^{-1}
Abatement cost/head J	$21,500	$20,000	$18,500	$17,500	$16,500
Global abatemt. cost H	$151 tr	$140 tr	$130 tr	$124 tr	$114 tr
H as % GDP	21.3%	19.8%	18.3%	17.5%	16.3%
Global inaction cost I	5-20%	2.2-8.6%	1.0-4.1%	0.7-2.7%	0.4-1.5%
Ratio H:I_{max}	1.1	2.3	4.5	6.5	10.9

Even the use of Stern's minimalist discount rate shows that the global abatement cost – i.e., the cost of forestalling all global warming between now and 2020 if all measures to mitigate global warming from all anthropogenic causes were as cost-effective as Dr. Garnaut's proposal – will exceed Stern's own estimated maximum cost of climate-related damage arising from worldwide inaction.

At Garnaut's own discount rates, the global abatement cost would be 2.3-4.5 times the inaction cost. At the Treasury's 3.5% discount rate, the global abatement cost would be almost 6.5 times the inaction cost. At President Klaus' recommended 5% discount rate, the cost of doing what Dr. Garnaut proposes would be an order of magnitude above the maximum cost of doing nothing.

Discussion

For the sake of simplicity and accessibility, the focus of the method is deliberately narrow. Potential benefits external to CO2 mitigation, or changes in global-warming potentials over long timescales, or relatively higher mitigation costs in regions with lower emission intensities, are ignored: little error arises.

Given the small quanta of warming forestalled by CO2-reduction policies, as well as the breadth of the intervals of published estimates of inaction and mitigation costs, greater complexity may in any event be otiose.

The case studies suggest official projections may be optimistic against the cost-effectiveness of specific policies. For instance, the abatement cost of EU carbon-trading is within Stern's inaction-cost interval, suggesting that the policy should be abandoned. The abatement cost of subsidy to the Thanet wind array, a large but typical government mitigation exercise, is well above the inaction-cost interval, *a fortiori* suggesting desubsidization. In general, smaller projects seem less mitigation-cost-effective than larger projects.

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 reducing M. However, within the 21st century even the immediate and total elimination of CO2 emissions will only forestall 1.7 K global warming.
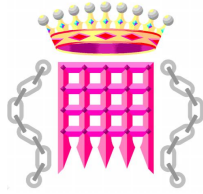
For numerous reasons, Eq. (1) and the case studies tend to overstate the warming that any CO2-reduction policy may forestall, and also to overstate mitigation cost-effectiveness:

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 forestalled by that year. The IPCC takes CO2's mean atmospheric residence time as 50-200 years: if so, little mitigation will occur within the 21st century. In some cases – for example, the EU carbon trading scheme – 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 backup 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 backup generation 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 forestalled may be less than shown. Though emissions are rising in accordance with the IPCC's A2 emissions scenario, concentration growth has been sub-exponential for a decade, so that outturn by 2100 may be considerably below the IPCC's A2-scenario low-end estimate 730 ppmv.

The A2 scenario is one of the more extreme emissions scenarios: use of any of the four less extreme scenarios would lead to lesser warming and hence to reduced mitigation cost-effectiveness. 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 forestalled would reduce mitigation cost-effectiveness.
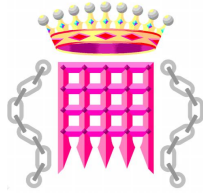
Conclusions

The case studies indicate that government estimates of overall abatement cost are likely to be optimistic. Mitigation policies cheap enough to be affordable will be ineffective, while policies costly enough to be effective will be unaffordable. It is unlikely that any policy to forestall 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. High abatement costs, and the negligible returns in warming forestalled, imply that focused adaptation to the consequences of such future warming as may occur will prove to be some orders of magnitude more cost-effective than any attempted mitigation. If so, since the opportunity cost of diverting trillions of dollars to mitigation is heavy, the question arises whether mitigation should be attempted at all.
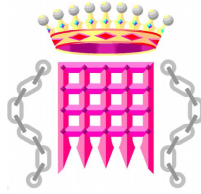
Acknowledgements

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