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Abstract

The Intergovernmental Panel on Climate Change (IPCC) has been criticised for using market exchange rates rather than purchasing power parity (PPP) exchange rates in its scenarios of future greenhouse gas emissions. PAGE2002, an integrated assessment model of climate change is used to show that neither the changes in regional GDP, nor the changes in emissions that might result, have any significant effect upon the social cost of carbon. The choice of market or PPP exchange rates is irrelevant for policy decisions on climate change that we need to take today.

Introduction

The social cost of carbon is the increase in future damage, discounted to the present day, that occurs if current emissions of carbon dioxide are increased by 3.75 tonnes. An increase of 3.75 tonnes of CO_2 emissions involves emitting an extra tonne of carbon, hence the name, although it must always be remembered that any values quoted only apply if the carbon is emitted as CO_2, not in any other form.

Several papers have investigated the social cost of carbon recently (Eyre et al, 1999: Tol, 1999; Clarkson and Deyes, 2002). An Integrated Assessment Model (IAM) of climate change (Hope, 2005a) and a scenario of future greenhouse gas emissions are required to make the necessary calculations.

The Intergovernmental Panel on Climate Change (IPCC) has produced a family of six illustrative scenarios in its Special Report on Emission Scenarios (SRES) (Nakicenovic & Swart, eds, 2000). One of these, Scenario A2, represents a very heterogeneous world, with an underlying theme of self-reliance and preservation of local identities (IPCC, 2001b, p63). As with all the IPCC illustrative scenarios, it assumes no active intervention to control emissions.

The IPCC has been criticised for using market exchange rates to convert base year and projected GDP to $US in its SRES scenarios including the A2 scenario (Castles and Henderson, 2002). The Economist has claimed that the use of market exchange rates rather than purchasing power parity (PPP) rates

> 'leads them to overstate the initial gaps in average incomes between rich and poor countries—because prices tend to be much lower in poor countries. Those gaps are in turn crucial for the IPCC's projections, because the method used in the scenarios assumes not only that the rich countries will continue to get richer but also, in most of the 40 scenarios considered, that the greater part of the (overstated) initial gaps between rich and poor will be closed by the end of the century.
>
> The combination of overstated gaps and of built-in assumptions about the extent of convergence in the average incomes of rich and poor countries yields projections of GDP for developing regions which are improbably high.' (Economist, 2003).

This critique has in turn been criticised for not allowing that emission intensities will change if PPP rates instead of market exchange rates are used, so that the effect upon emission projections may not actually be large (Alfsen et al, 2003).

So there are two issues to be explored:

Is the social cost of carbon affected if the level and growth rates of GDP have been projected using market exchange rates rather than PPP ones?

Is the social cost of carbon affected if the emissions of CO_2 from a scenario have been over-estimated because projections have used market exchange rates rather than PPP ones?

The PAGE2002 integrated assessment model

PAGE2002 is an updated version of the PAGE95 integrated assessment model (Plambeck, Hope and Anderson, 1997, Plambeck and Hope, 1995 and Plambeck and Hope, 1996). The main structural changes in PAGE2002 are the introduction of a third greenhouse gas and the incorporation of possible future large-scale discontinuities into the impact calculations of the model (IPCC, 2001a, p5). Default parameter values have also been updated to reflect changes since the IPCC Second Assessment Report in 1995.

PAGE2002 contains equations that model:

* Emissions of the primary greenhouse gases, CO2 and methane, and a third gas, SF6 in this investigation. PAGE2002 models other greenhouse gases such as N_2O and (H)CFCs as a time-varying addition to background radiative forcing.

* The greenhouse effect. Anthropogenic emissions of greenhouse gases exceed the rate of removal by chemical and biological processes and accumulate in the atmosphere. The greenhouse gases trap heat in the atmosphere so that less of the incoming solar radiation is re-radiated to space. This increases radiative forcing, the net flux of energy to Earth. The Earth's temperature rises very slowly as excess heat is transferred from the atmosphere to land and ocean.

* Cooling from sulphate aerosols. Sulphate aerosols result from fossil fuel combustion and are commonly known as the cause of acid rain. They also backscatter incoming solar radiation and interfere with cloud formation, producing a direct and indirect reduction in radiative forcing. This counteracts the greenhouse effect.

* Regional temperature effects. Unlike greenhouse gases which remain in the atmosphere for decades and are globally mixed, sulphate aerosols have a very short atmospheric lifetime (about 6 days) and so tend to remain in the source region. Therefore sulphate aerosol cooling is a regional phenomenon. For the eight world regions in PAGE2002, temperature rise is computed from the difference between global warming and regional sulphate aerosol cooling. Sulphate cooling is greatest in the more industrialised regions, and tends to decrease over time due to sulphur controls to prevent acid rain and negative health effects.

* Nonlinearity and transience in the damage caused by global warming. Climatic change impacts in each analysis year are a polynomial function of the regional temperature increase in that year above a time-varying tolerable level of temperature change, $(T-T_{tol})^n$, where n is an uncertain input parameter. If the temperature rises beyond another threshold, there is a chance that a large-scale climate discontinuity will occur with very serious effects; the more the temperature rises beyond the threshold, the larger the chance of the discontinuity occurring.

* Regional economic growth. Impacts are evaluated in terms of an annual percentage loss of GDP in each region, for a maximum of two sectors- in this application defined as economic impacts and non-economic (environmental and social) impacts.

* Adaptation to climate change. Investment in adaptive measures (e.g. the building of sea walls; development of drought resistant crops) can increase the tolerable level of temperature change (T_{tol}) before economic losses occur and also reduce the intensity of both noneconomic and economic impacts.

The PAGE2002 model uses relatively simple equations to capture complex climatic and economic phenomena. This is justified because the results approximate those of the most complex climate simulations, as shown below, and because all aspects of climate change are subject to profound uncertainty. To express the model results in terms of a single 'best guess' could be dangerously misleading. Instead, a range of possible outcomes should inform policy. PAGE2002 builds up probability distributions of results by representing 31 key inputs to the marginal impact calculations by probability distributions, making the characterisation of uncertainty the central focus, as recommended by Morgan and Dowlatabadi (1996).

The full set of equations and default parameter values in PAGE2002 are given in Hope, forthcoming. Most parameter values are taken directly from the IPCC Third Assessment Report (IPCC, 2001a and b), and the model closely reproduces the concentration, forcing and climate results of the Scenario A2 from the IPCC Special Report on Emission Scenarios (SRES) (Nakicenovic & Swart, 2000; Hope, forthcoming).

Social cost of carbon calculations

In this investigation, PAGE2002 is run with global emissions of greenhouse gases from Scenario A2 of the IPCC (IPCC, 2001b, p64). This scenario is chosen because it was one of two investigated in sufficient depth in the IPCC's Third Assessment Report to allow detailed comparisons with the PAGE2002 results (IPCC, 2001b, p531). Because the model continues to calculate impacts to 2200, emissions are assumed to remain constant after 2100, the end point of the A2 scenario.

The agreement between the PAGE2002 mean global mean temperature results and the IPCC reference results for scenario A2 is excellent – within 0.1 degC for all years up to the end of the IPCC's calculations in 2100 (Hope, forthcoming).

Using market exchange rates, the gross world product is $31.8 trillion in 2000 (IMF, 2000). Scenario A2 gives the regional breakdown in 1990 and 2020 for the four regions of OECD, EFSU, Asia and RoW. Assuming the breakdown in 2000 is one-third of the way between the 1990 and 2020 values, and that the breakdown inside the four regions is the same as when measured in PPP rates, the base year GDP at market exchange rates for the eight PAGE2002 regions can be estimated.

Equity weights

Clarkson and Deyes, 2002, justify equity weighting as follows:

> 'The effect of equity weighting is that it allows welfare equivalents to be compared since a dollar to a poor man is worth more than a dollar to a rich man. Therefore, it accounts for the fact that if a poor person were to be

given an amount of money, then he/she would value that money far more than if it were given to a person who already was very rich.' (Clarkson and Deyes, 2002, box 1)

The exact form used in the Eyre et al (1999) study, on which Clarkson and Deyes is based, is to multiply the impacts in a region by

$$(Y_{world}/Y_{region})^{-elasticity}$$

where Y is the GDP per capita and 'elasticity' is the elasticity of marginal utility with respect to income, taken to have a value of -1. The effect is to increase the impacts in poor regions of the world, and reduce the impacts in rich regions; since most climate change impacts are expected to occur in poor regions of the world, the overall effect of using equity weights is to increase the impacts and thus the social cost of carbon.

The standard form of the PAGE2002 model does not include equity weights, but it is a relatively simple matter to introduce them in the form shown here, and table 1 shows the resulting social cost of carbon, with no discontinuities and a constant SRTP of 3% per year. The social cost is shown for two values of the marginal elasticity of utility with respect to income, a value of –1 as used in Clarkson and Deyes, and a value of –0.5 which takes into account the criticisms in Pearce, 2001, as well as for no equity weighting.

Table 1 The social cost of carbon with equity weights and market exchange rates

No discontinuities, 3% SRTP			*$(2000)/tC*
	5%	mean	95%
Elasticity = -1	10	43	124
Elasticity = -0.5	8	35	104
No equity weights (elasticity = 0)	8	31	92

Source: PAGE2002 V1.4e

The mean social cost of carbon for an elasticity of –1 is $43 per tonne. This is lower than the central value of £70 per tonne proposed by Clarkson and Deyes (2002), but in line with other estimates such as Tol (1999).

Clarkson and Deyes (2002) claimed that equity weighting gives marginal damage at least a factor of two higher than if regional damages are not equity weighted. This is not borne out by the PAGE2002 results, which show equity weighting increasing the social cost of carbon by only about one third.

Table 2 shows the equity weights in 2000 and 2100 for an elasticity of -1. They imply that in 2000, a dollar's worth of impacts in India and South Asia should be weighted 34 times as highly as a dollar's worth of impacts in the United States or 'other OECD'.

By 2100, the range of equity weights reduces considerably; impacts in India and South Asia are now weighted 6.5 times as highly as in the United States, and 13 times as highly as in 'other OECD'. As the main contribution to the social cost of carbon comes from impacts in the latter half of the century, this is the main reason that equity weighting does not have a greater effect.

Table 2 Equity weights by year with market exchange rates

Elasticity = -1	2000	2100
European Union	0.3	0.3
Eastern Europe and former Soviet Union	2.2	0.9
United States	0.2	0.4
China and centrally planned Asia	3.9	1.6
India and South Asia	6.8	2.6
Africa and Middle East	2.0	1.3
Latin America	1.1	0.6
Other OECD	0.2	0.2
Mean	1.0	1.0

Source: A2 scenario in PAGE2002 V1.4e

PPP rather than market exchange rates

If Castles and Henderson (2002) are right, what is really required is to use the base year PPP rate regional GDPs that are already in PAGE2002 with a version of scenario A2 whose GDP growth rates have been converted from market exchange rates to PPP rates. This is what is done in table 3 (the details of the adjustment to scenario A2 are shown in the appendix).

The social costs of carbon that result are slightly larger than the values in table 1 using market exchange rates. This is mainly because the year 2000 GDP in poor regions is higher using PPP exchange rates, giving a gross world product at $43.8 trillion. But the difference between the market exchange rate GDP and the PPP GDP declines over time, until they are nearly equal in 2100. As the main contribution to the social cost of carbon comes from impacts in the latter half of the century, the differences in the social cost of carbon are small.

Table 3 The social cost of carbon with equity weights and PPP exchange rates

No discontinuities, 3% SRTP			*$(2000)/tC*
	5%	mean	95%
Elasticity = -1	10	46	118
Elasticity = -0.5	9	37	104
No equity weights (elasticity = 0)	8	32	90

Source: PAGE2002 V1.4e

Table 4 shows the equity weights. The year 2100 weights are the same as in table 2, since the way in which scenario A2 was adjusted preserved the ratios of other regions GDP to that of the US in 2100, but the weights for the poor regions in 2000 are now smaller, as their GDP per capita is larger when using PPP rates than when using market exchange rates.

Table 4 Equity weights by year with PPP exchange rates

Elasticity = -1	2000	2100
European Union	0.3	0.3
Eastern Europe and former Soviet Union	1.6	0.9
United States	0.2	0.4
China and centrally planned Asia	1.7	1.6
India and South Asia	3.2	2.6
Africa and Middle East	1.9	1.3
Latin America	1.0	0.6
Other OECD	0.2	0.2
Mean	1.0	1.0

Source: adjusted A2 scenario in PAGE2002 V1.4e

Lower emissions

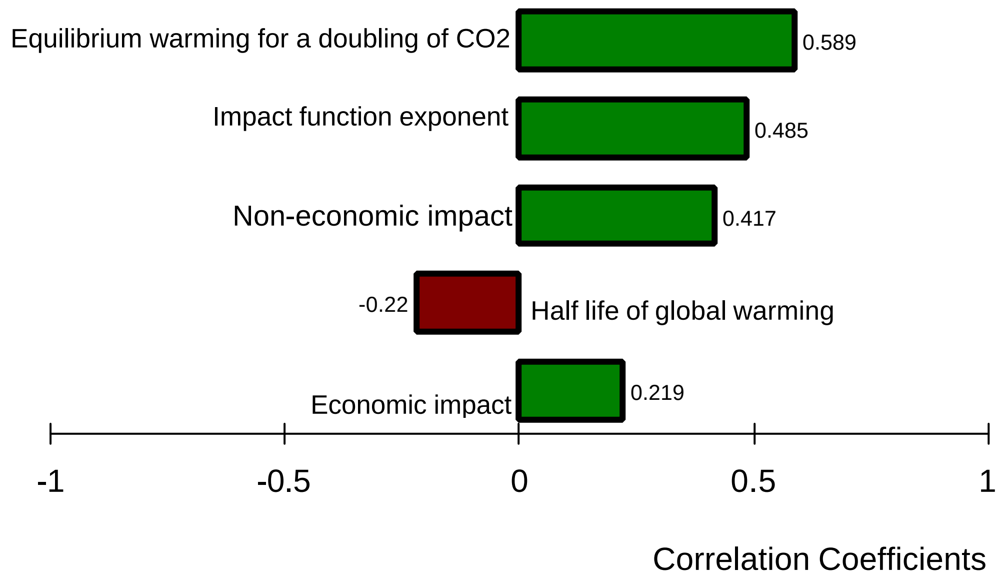
How about the second criticism of Castles and Henderson, that the emissions from the SRES scenarios may have been overestimated? Even if we make an extreme assumption about the inaccuracy of scenario A2, namely that global emissions of CO2 in all future years are only half the values assumed in Scenario A2 from the SRES, the results from PAGE2002 show that today's social cost of carbon is essentially identical to the A2 value, with a mean value of $45 and a 5 – 95% range of $11 – 110 for a 3% SRTP and elasticity of –1.

This insensitivity of SCC to the emission path is rather counter-intuitive and is a strong argument for using an integrated assessment model, as neither a scientific nor an economic model would pick it up. It is caused by the interplay between the logarithmic relationship between forcing and concentration (which will tend to make one extra tonne under the lower concentrations of the 'half A2' scenario cause more damage), the non-linear relationship of damage to temperature (which will tend to make one extra tonne under the higher temperatures of the A2 scenario cause more damage), and discounting (which will tend to make early damage more costly than late damage) (Hope, 2005b).

It essentially means that any inaccuracy in the emissions of the SRES scenarios, even as extreme as an overestimation of emissions by a factor of two, is irrelevant for policy decisions that we need to take today.

So neither of the two issues identified at the start of this paper would seem to have a significant effect upon today's social cost of carbon. Certainly, any effect is greatly outweighed by our lack of knowledge of many of the variables associated with climate change, such as the climate sensitivity to a doubling of CO2 concentrations, or the shape of the impacts as a function of temperature rise. Figure 1 shows the major influences.

Figure 1 Major influences on the social cost of carbon



An example shows the changes to today's social cost of carbon that new scientific information can bring. Using the recent likelihood-weighted probability distribution for the climate sensitivity from Murphy et al (2004), with a mean value of 3.6 degC, and a 5-95% range of 2.4 to 5.4 degC, instead of the 1.5 to 5.0 degC range given by the IPCC (2001b), increases the mean value of the SCC with PPP exchange rates from \$46 to \$64 per tonne of carbon, with a 5-95% range of \$12 - 175.

Further work

There are two further considerations. The results presented in this paper have been calculated using a single value for the SRTP, 3% per year. However, the SRTP can be derived from the pure rate of time preference, the per capita GDP growth rate, and the marginal elasticity of utility with respect to income, using the Ramsey rule:

SRTP = PTP + e*g

where PTP is the Pure Time Preference rate,
e is the negative of the elasticity of marginal utility with respect to income, and
g is the per capita GDP growth rate (Plambeck and Hope, 1996).

Now, if the per capita GDP growth rate changes because of the move to PPP exchange rates, this can have an effect on the discount rate, and so on the social cost of carbon.

Also, the elasticity used in the equity weighting formula is exactly the same parameter as is used in the derivation of the discount rate using the Ramsey rule, so it is not at all clear that we have the freedom to alter the elasticity value in the equity weighting formula while keeping a constant SRTP. A more consistent approach is to specify the PTP rate and elasticity that we wish to use, and derive consistent equity weights and SRTP values.

These two further considerations will be the subject of future investigations with PAGE2002.

Acknowledgement

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Appendix: Adjustments to the A2 scenario GDP growth rates to incorporate purchasing power parity

The GDP growth rates in the published A2 scenario use market exchange rates to convert national currencies to $US. The IMF and OECD, amongst others, have recommended that purchasing power parity rates should be used, which reflect the difference in prices in different countries. This appendix describes the procedure used in this paper to adjust the market exchange GDP growth rates in scenario A2 to purchasing power parity (PPP) growth rates.

The three assumptions made were:

- Growth rates in the US are the same when measured in market exchange or PPP rates, as the $US dollar is the numeraire.
- The ratio of GDP per capita in each region to the world average in 2100 is the same when measured in market exchange or PPP rates. This is reasonable as the A2 scenario is driven by 'closing the gap' between developed and developing country GDP.
- In each region, PPP GDP grows at a constant rate from 2000 to 2040, and a different, lower, constant rate from 2040 to 2100. This reflects approximately the pattern of growth rates in the original A2 scenario.

Table A1 shows the GDP growth rates in the original A2 scenario

Table A1 GDP growth rates by region and time period (% per year)

start	2000	2001	2002	2010	2020	2040	2060	2080
end	2001	2002	2010	2020	2040	2060	2080	2100
EU	1.8	1.8	1.8	1.5	1.8	1.1	1.6	1.7
EE	2.4	2.4	2.4	3.2	4.1	2.2	2.8	2.6
US	1.8	1.8	1.8	1.5	1.8	1.1	1.6	1.7
CA	4.4	4.4	4.4	4.2	4.4	2.3	2.8	2.5
IA	4.4	4.4	4.4	4.2	4.4	2.3	2.8	2.5
AF	4.0	4.0	4.0	4.4	4.6	2.3	2.8	2.3
LA	4.0	4.0	4.0	4.4	4.6	2.3	2.8	2.3
OT	1.8	1.8	1.8	1.5	1.8	1.1	1.6	1.7

Source: Nakicenovic and Swart, 2000

Table A2 shows the population and GDP at market exchange rates (GDPm) and PPP rates (GDPp) in 2000.

Table A2 Population and GDP in 2000

	Pop (million)	GDPm ($trillion)	GDPp ($trillion)
EU	400	7.90	8.76
EE	600	1.40	2.63
US	300	8.90	9.64
CA	1300	1.70	5.26
IA	2000	1.50	4.38
AF	800	2.10	3.07
LA	500	2.40	3.50
OT	200	5.90	6.57
total	6100	31.8	43.8

Source: IMF, 2000

Table A3 shows the population growth rates in Scenario A2.

Table A3 Population growth rates by region and time period (% per year)

start	2000	2001	2002	2010	2020	2040	2060	2080
end	2001	2002	2010	2020	2040	2060	2080	2100
EU	0.4	0.4	0.4	0.3	0.2	0.1	0.3	0.4
EE	0.4	0.4	0.4	0.3	0.4	0.5	0.6	0.6
US	0.9	0.9	0.9	0.9	0.7	0.7	0.8	0.9
CA	1.1	1.1	1.1	1.0	0.9	0.8	0.8	0.6
IA	1.7	1.7	1.7	1.4	1.1	0.7	0.4	0.1
AF	2.7	2.7	2.7	2.4	1.9	1.3	0.7	0.3
LA	1.8	1.8	1.8	1.6	1.4	1.1	0.9	0.8
OT	0.5	0.5	0.5	0.1	0.1	0.0	0.2	0.3

Source: Nakicenovic and Swart, 2000

These values allow the US year 2100 GDPm of $41.7 trillion and the ratios of GDP per capita in all regions to be found, as shown in table A4.

Table A4 ratios of GDPm/cap to world average in 2100

EU	3.1
EE	1.1
US	2.8
CA	0.6
IA	0.4
AF	0.8
LA	1.6
OT	5.1

If the US GDPp grows at the same rate as GDPm it will reach $45.1 trillion in 2100. Keeping the same ratios of GDPp/cap as GDPm/cap, gives the regional values for GDPp in table A5.

Table A5 GDPp in 2100 ($trillion)

EU	40.1
EE	26.5
US	45.1
CA	46.0
IA	40.6
AF	55.6
LA	63.6
OT	29.9

Let g1 be the annual growth rate in GDPp from 2000 to 2040, g2 be the annual growth rate in GDPp from 2040 to 2100, then

GDPp(2100) = GDPp(2000)*exp(40g1 + 60g2)

So 40g1 + 60g2 = ln(GDPp(2100)/ GDPp(2000))

Let g2 = (1 + f)g1

Then 40g1 + 60(1 + f)g1 = ln(GDPp(2100)/ GDPp(2000))

So g1 = ln(GDPp(2100)/ GDPp(2000))/(100 + 60f)

From inspection of table A1,

let f = -0.1 for developed regions (EU, EE, US, OT), and

let f = -0.4 for developing regions (CA, IA, AF, LA).

This procedure gives the growth rates for GDPp shown in table A6. These are the GDP growth rates used as inputs to PAGE2002 to adjust scenario A2 to PPP rates. As can be seen by comparing table A6 with table A1, the adjustments are small in the developed regions and up to about 1.5 % per year in developing regions, with the largest adjustments in China and India, as expected. The global average growth rate for 2080 to 2100 is 1.9 % per year, and this is used for all regions for the period 2100 to 2200.

Table A6 GDPp growth rates by region and time period (% per year)

start	2000	2001	2002	2010	2020	2040	2060	2080
end	2001	2002	2010	2020	2040	2060	2080	2100
EU	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5
EE	2.5	2.5	2.5	2.5	2.5	2.2	2.2	2.2
US	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5
CA	2.9	2.9	2.9	2.9	2.9	1.7	1.7	1.7
IA	2.9	2.9	2.9	2.9	2.9	1.8	1.8	1.8
AF	3.8	3.8	3.8	3.8	3.8	2.3	2.3	2.3
LA	3.8	3.8	3.8	3.8	3.8	2.3	2.3	2.3
OT	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5

Source: author's calculation