Review of DEFRA paper: "The Social Cost of Carbon and the Shadow Price of Carbon: what they are, and how to use them in Economic Appraisal in the UK"

Simon Dietz

- Department of Geography and Environment and Centre for Environmental Policy and Governance, London School of Economics and Political Science (LSE), Houghton Street, London WC2A 2AE
- Tyndall Centre for Climate Change Research, University of East Anglia (UEA), Norwich

Contact details: e-mail: s.dietz@lse.ac.uk
tel.: +44 (0) 207 955 7589
fax: +44 (0) 207 955 7412

Summary

This paper sets out my comments on DEFRA's new guidance on how to price greenhouse gas emissions – 'carbon' for short – into economic appraisal in the UK. The DEFRA paper begins by drawing a distinction between the social cost of carbon and the shadow price of carbon for use in government economic appraisal in the UK. While the terminology is confusing, this is an improvement on previous guidance, because it correspondingly draws a distinction between setting overall government policy on greenhouse gas emission reductions (by how much and when?), and internalising the cost of emissions in what we might call 'everyday', or marginal, applications of economic appraisal. This liberates the discussion from more fundamental debates about the social cost of carbon and its role in formulating policy (see comments by Barker and Ekins on previous reports commissioned by DEFRA), and leads to the following observations:

- For the purposes of 'everyday' policy and project appraisal, the most important objective is to be consistent with the overall policy of the UK government on greenhouse gas emission reductions;
- If present government guidelines on appraisal encourage cost-benefit analysis, then the shadow value of emissions must be estimated, or else the implications of a particular investment for climate change will not be taken into account. Any further fundamental

objections to the pricing of carbon would be better directed at the larger practice of economic appraisal in government;

- There are many reasons why overall government policy on emission reductions will not be optimal in the terms of models estimating the social cost of carbon;
- There is an unavoidable need to make assumptions about present and future government policies in the UK and in the rest of the world, if the shadow price of carbon is to be consistent with those policies.

The DEFRA paper goes on to make assumptions about the future trajectory of atmospheric concentrations of greenhouse gases, which would result from present government policy in the UK, linked with emission reductions made in the rest of the world. These seem defensible. Therefore there is much to commend in the paper's initial approach to the problem.

My principal concern is with the approach then taken by DEFRA to estimate the shadow price of carbon, based on the social cost of carbon estimated by the Stern Review. Admittedly, this estimate has two advantages. First, it is consistent with the value judgements – especially on intergenerational equity – that arguably underpin the UK government's policy on climate-change mitigation. Second, it is based on a model and method, which summarises disagreement and uncertainty in scientific and economic research on climate change: it is probably a good central estimate. Yet the uncertainty around empirical estimates of the social cost of carbon spans perhaps three orders of magnitude (Downing *et al*., 2005), so we ought to place very little confidence in any estimate. Since the uncertainty around empirical estimates of the marginal abatement cost of carbon is perhaps two orders of magnitude *less*, I think there is a strong case for using marginal abatement costs as an additional source of information. Finally, recent, largely theoretical work has raised some difficult questions about the numéraire used for the social cost of carbon: different answers lead to very different estimates, and there is a similar need to think more carefully about this issue.

A minor concern lies with the approach taken to estimate the social cost of emitting greenhouse gases other than carbon dioxide. Multiplying the social cost of carbon by the relevant global warming potential is a poor approximation of directly estimating the social cost of e.g. methane. Where direct estimates exist, these should be used.

The social cost of carbon and the shadow price of carbon

The social cost of carbon (SCC) is taken to mean the full effect on social welfare of emitting an extra tonne of carbon (as carbon dioxide) at some point in time, over the lifetime of that tonne in the atmosphere. To be more precise, it is the marginal damage cost of carbon (MDC). As a measure of welfare change, the SCC needs a numéraire. It is always expressed in relation to consumption at the time when the marginal tonne is emitted and, on the whole, it measures global effects on social welfare and expresses them in relation to global consumption (but it is not inevitable that global effects are of interest, nor that global consumption is the appropriate numéraire: see below). Often, the SCC is used as shorthand for the social cost of emitting other greenhouse gases. Here, I will follow this convention, except where I discuss explicitly how to calculate the social cost of emitting greenhouse gases other than carbon dioxide. Calculating the SCC requires quantification of the whole process linking anthropogenic emissions of greenhouse gases with impacts on social welfare, normalised to impacts on consumption. This is a heroic task performed by "integrated assessment models".

In economic appraisal of public investments, the aim is to value changes in the emission of greenhouse gases at their shadow prices. The shadow price of any good is the increase (decrease) in social welfare brought about by providing one more (less) unit of that good. Thus the shadow price of carbon (SPC) is defined as the social cost of emitting a marginal tonne of carbon (or the social benefit of abating a tonne), just like the SCC. But we know from the general economic theory of project evaluation that the values taken by shadow prices depend on the level of public production at which they are evaluated (Drèze and Stern, 1990). The shadow price at the optimum level of public production is different to the shadow price away from the optimum. In many traditional applications of cost-benefit analysis, this may not be of any great consequence, because nearly all of the variables affecting the overall level of public production are outside the control of the planner.

This is not the case in climate-change policy and herein lies the difficulty. Greenhouse gases are stock pollutants and the SPC/SCC depends not only on the atmospheric stock or concentration of greenhouse gases at the time of emission, but also on future concentrations over the atmospheric lifetime of the gas (i.e. it is path-dependent), which can be a century or more. We would not expect the SPC or SCC at the optimum level of greenhouse gas emissions to equal the SPC or SCC at a level away from the optimum, since the differences in climate-change damages on different emissions paths could be large, while policy choices determine the level of emissions. We should hence measure the SPC/SCC at the actual (not necessarily optimal) level of emissions, and because the SPC/SCC is path-dependent, we cannot estimate the SPC/SCC today without making an assumption about the future path of GHG emissions.

It is precisely this issue that the DEFRA paper is concerned with, and it is to be commended for doing so. I find the terminology confusing though. Most generally, the definition of the SPC is the same as the SCC and there will be as many shadow prices as there will be emissions paths, just like the SCC. The concern is with the difference between optimal policies – in the very narrow sense of the intertemporally efficient policy in a particular integrated assessment modelling study – and actual policies. This difference might be better articulated.

Previous empirical estimates of the SCC have, broadly speaking, made one of two assumptions about the future path of emissions (see Clarkson and Deyes, 2002, and Pearce, 2005). The first type of study estimates the SCC along a business-as-usual path of emissions. This has been termed a 'marginal-cost' approach (Clarkson and Deyes, 2002), although the terminology is not particularly helpful. Such estimates could be used in government economic appraisal, but in order to be consistent with actual government policy, the government (together with the governments of the rest of the world, since climate-change mitigation is a global public good) would need to be pursuing a 'do-nothing' strategy on climate-change mitigation. This does not appear to be the case.

The second type of study determines the path of greenhouse gas emissions that maximises social welfare over all time-periods – the optimum path intertemporally – and estimates the SCC along that path. Clarkson and Deyes (2002) call this a 'cost-benefit' approach. Such estimates could be used in appraisal, but in order to be consistent with actual government policy, the government (together with the governments of the rest of the world) would need to have committed to an optimum path of emission reductions. Moreover, this path would have to be optimal in the terms of the integrated assessment modelling study or studies in question, which seems unlikely on at least three counts.

First, quantification of the SCC is highly uncertain and it is impossible to observe the probabilities of various uncertain climate impacts. This problem was extensively discussed in the two papers commissioned for DEFRA's recent review of the SCC (Downing *et al.*, 2005;

Watkiss *et al*., 2005). Government policy may choose to take into account impacts of climate change that are not quantified in estimating the SCC, or else make an alternative assessment of probabilities. Second, quantification of the SCC involves various value judgements, notably on equity within and between generations. There are no *a priori* answers to these ethical questions, so even if we could measure the impacts of climate change with scientific certainty, there can still be disagreement over the SCC. Third, quantification of the SCC more generally assumes that government policy on climate-change mitigation is decided on the basis of some form of utilitarian social-welfare objective, whereas in reality a wider range of factors is highly likely to play a role. Indeed, all of this is borne out by the fact that, based on a reading of current official targets (whether legally binding or aspirational), the UK government has set a more aggressive goal for emission reductions than would be recommended by most existing optimising studies. It is often pointed out that studies of optimal emission reductions do not recommend strong and urgent action (e.g. Tol and Yohe, 2006), whereas recent government policy is aiming for just that.

Why does the social cost of carbon depend on the future path of emissions?

Several previous studies have pointed out that the SCC is path-dependent (e.g. Clarkson and Deyes, 2002; Pearce, 2005). However, there has been little empirical analysis to support the theory, because most studies have either estimated the SCC on a business-as-usual emissions pathway, or estimated it on an optimal emissions pathway (based on its particular assumptions and social-welfare objective), but not on both. Moreover, of the empirical analyses that have compared approaches, Hope (2005) found that the SCC was independent of the future path of emissions, as did Maddison's (1994) older study. The Stern Review (Stern, 2007), on the other hand, found that the SCC was strongly path-dependent (table 1). In particular, it found that the SCC on a business-as-usual path was considerably higher than that on a path where strong emission reductions were made to stabilise the atmospheric concentration of greenhouse gases.

Table 1. Stern Review estimates of the SCC on different emissions paths, using PAGE2002. Three stabilisation scenarios are presented, with the target concentration of greenhouse gases in the atmosphere expressed in parts per million of carbon dioxide equivalent (ppm CO_2e).

Scenario	SCC (year 2000 $/tC)
Business-as-usual (baseline climate)	309.50
650ppm CO_2e stabilisation	143.65
550ppm CO_2e stabilisation	115.70
450ppm CO_2e stabilisation	89.20

The relationship between the SCC and the future path of greenhouse gas emissions is determined by the combination of a number of more specific relationships in the overall process linking emissions with social costs. To what extent the SCC depends on the path of emissions is an empirical question. The first is the logarithmic relationship between the atmospheric concentration of greenhouse gases and radiative forcing (loosely speaking, the difference between incoming and outgoing radiative energy in the climate system). The higher (lower) the atmospheric concentration of greenhouse gases, the lower (higher) the warming caused by an extra tonne of carbon, although because of the high thermal inertia in the climate system, the difference only becomes apparent after several decades have passed. The second is the relationship between warming and the economic impacts of climate change. This is generally assumed to be convex (i.e. damage increases more than proportionately with rising temperatures), so the higher (lower) temperatures, the higher (lower) the damage caused by an extra tonne of carbon. The third is discounting. The earlier (later) in relation to the point of emission that the impacts of climate change are experienced, the more (less) they are valued (unless consumption growth is sufficiently negative, which is highly unlikely). The longer it takes for differences in the undiscounted social costs to appear on different emissions paths, the less those differences will be apparent in the discounted SCC.

For the Stern Review results to hold, the logarithmic relationship between the atmospheric stock of greenhouse gases and radiative forcing must be outweighed by the convex relationship between warming and climate impacts. This begs the question why Hope's (2005) result is different to Stern's, especially since both studies used the same integrated assessment model (PAGE2002). With similar emissions scenarios[1], the primary explanation

[1] Both studies estimate business-as-usual emissions on the IPCC SRES A2 scenario (Nakicenovic and Swart, 2000), but Stern's stabilisation scenarios are more successful at controlling the atmospheric stock of greenhouse gases than are Hope's. Stern's scenarios control the total concentration of a basket of greenhouse gases, whereas Hope only controls carbon dioxide, so business-as-usual emissions of the other

ought to be discounting and, in explaining why, it is worthwhile reminding readers of the standard formula for the social rate of time preference:

$$r(t) = \eta g(t) + \delta \qquad (1)$$

r is the social rate of time preference (equal here to the social discount rate), η is the elasticity of the social marginal utility of consumption, *g* is the growth rate of consumption per capita and δ is the rate of pure time preference. What is most important for our purposes is to note that the social discount rate is neither constant nor certain: it depends if nothing else on future consumption growth. Moreover, if we assume climate change itself possesses the capacity to depress consumption growth on a global scale, then the choice of social discount rate is not *exogenous* to the choice of climate-change policy.

In Stern, the discount rate applied to any one of PAGE2002's scenarios (i.e. any one of its 1000 model-runs) depends on growth in that scenario, and thus on the impacts of climate change. But in Hope (2005), as in most of the previous literature, a single discount rate is applied to all scenarios, which often implies that the growth rate assumed for the purposes of discounting is inconsistent with the growth rate in the model (except where the impacts of climate-change are negligible). The effect is to impose uniformity on the SCC across different emissions scenarios (Dietz *et al*., 2006, report a full set of results). The difference between sets of estimates of the SCC produced with endogenous discounting (as in Stern) and those produced with exogenous discounting (as in Hope, 2005, and most other studies) is large if the discount rate is low, because the differences occur with a time lag. If the discount rate is high, the differences are small and since the previous literature commonly used higher discount rates, this also explains why the finding of path-dependency is relatively new. Figures 1a and 1b demonstrate this.

greenhouse gases in Hope's scenarios drive the atmospheric stock beyond the intended stabilisation goal. In addition, Hope assumes that emissions of sulphate aerosols, which have a cooling effect, fall in line with emissions of carbon dioxide, while Stern does not. In this last respect, Hope's assumption appears more sensible.

Figure 1a. Difference between marginal damage cost estimates for endogenous and exogenous discounting, δ=0.1% p.a., η=1.

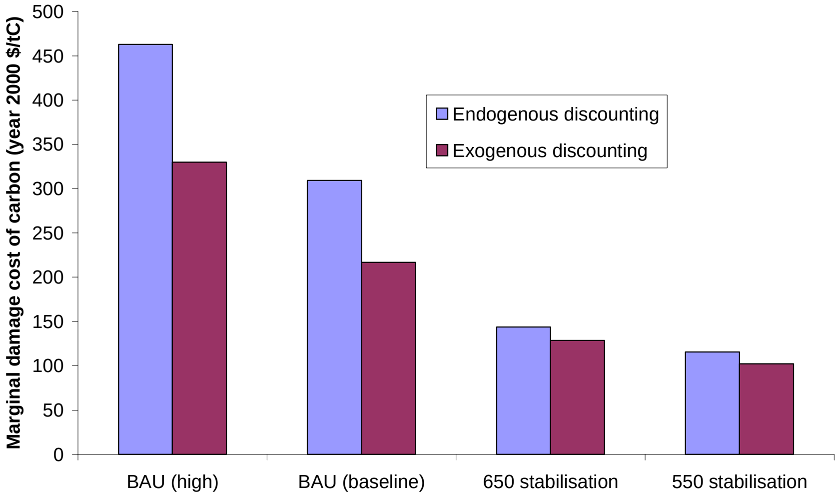
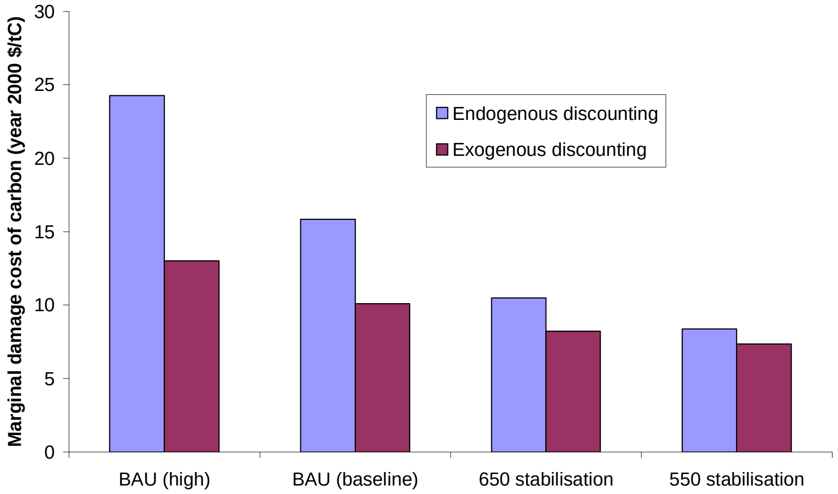


Figure 1b. Difference between marginal damage cost estimates for endogenous and exogenous discounting, δ=1.5% p.a., η=2.



What policy path are we on?

The important question remains; what policy path are we on? Here it is important to think about areas of control. As with the theory of shadow prices more generally, the SPC depends on the areas of government policy that are under the control of the planner in question, and those that are not (Sen, 1972). These issues have typically been raised in relation to national policy: what happens, for example, if important policy variables such as taxes and trade tariffs are outside the project planner's control? In this case, however, we are not so much interested in areas of control within national policy. In mitigating climate change, the prospects of securing cross-governmental action towards objectives may be no more or less realistic than in any other area of policy, although perhaps there is more hope of coordination here, since large emission reductions that are at the same time cost-effective are likely to require a host of policies across most sectors of the economy and most government departments and agencies will need to be involved. Instead, we are more concerned with the amount of control a national government can exercise, using its domestic policy, over global policy and consequently over global results, in terms of the atmospheric stock of greenhouse gases. As a first cut, we might assume policy outside the UK is outside the planner's control and in turn that the atmospheric concentration of greenhouse gases is also an outcome outside the UK planner's control, even with strong domestic efforts. Climate-change mitigation is a global public good and a medium-size emitter such as the UK (around 2% of total global emissions and falling) can achieve virtually nothing on its own. But the situation is more complicated than that, if it is believed that, in taking an acceptable share of the burden of emission reductions, the UK can stimulate other countries to make their own efforts (i.e. provide leadership).

Strictly to elaborate the theory, a spectrum of assumptions seem possible, from business-as-usual, to stabilisation at, say, 450-550 parts per million of carbon dioxide equivalent (we have already passed 430 ppm CO_2e). Table 2 explores four extreme possibilities, dividing global efforts into those of the UK and those of the rest of the world.

Table 2. Assumptions about future emissions of greenhouse gases in the UK and the Rest of the World.

450-550 stabilisation UK cuts emissions Rest of the World cuts emissions	**Business-as-usual** UK cuts emissions Rest of the World does not cut emissions	UK efforts ↑
450-550 stabilisation UK does not cut emissions Rest of the World cuts emissions	**Business-as-usual** UK does not cut emissions Rest of the World does not cut emissions	
← Rest of the world's efforts		

Since the greenhouse gas emissions of the rest of the world dwarf those of the UK (currently 44:1 and rising), everything depends on the former. If the rest of the world does not cut emissions consistent with stabilisation at 450-550 ppm CO_2e, the world will not achieve this target range, irrespective of what the UK does. Conversely, if the rest of the world does, and the UK succeeds in free-riding on the rest of the world's efforts, the world will achieve this target range. The more realistic scenarios in table 2 appear to be in the top left and bottom right quadrants. If the UK and the rest of the world both deliver emission reductions consistent with stabilisation at 450-550 ppm CO_2e, the world will self-evidently achieve this range.

Conversely, if neither the UK nor the rest of the world act, emissions will follow a business-as-usual trend.

The task is to read off a long-run trajectory for the atmospheric stock of greenhouse gases that is consistent with current UK policy, which is not explicit on greenhouse gas concentrations, rather setting targets for the annual flow of emissions in a future year (e.g. 2012, 2020, 2050). In addition, we must make a similar and linked reading of what the rest of the world will do, because UK emissions alone are insufficient to affect the atmospheric stock in the future. The DEFRA paper assumes that UK policy and policies in the rest of the world put us on a path to stabilising the atmospheric stock of greenhouse gases at 550 ppm CO_2e. I agree this seems a reasonable starting point. It lies at the high end of the stabilisation range recommended by the Stern Review (Stern, 2007), and seems consistent with the government's present, long-run target. That target has in turn been set in anticipation of compatible mitigation in the rest of the world, and indeed is arguably intended to show leadership.

Pessimists might well contend that, while the UK is on such a path, the rest of the world is not and will not be. But if that were the conviction of UK government policy, then the UK's own long-run target (a soon-to-be mandatory 60% cut in carbon emissions by 2050, compared with 1990 levels) is doomed to fail and would presumably be abandoned. This reading is inconsistent with current government policy. They may on the other hand contend that the UK will not deliver on its long-run target, but here there is a problem of circularity: it is indeed unlikely to, if public sector investments don't price in its climate-change objectives.

How much do we know about the social cost of carbon?

My concerns begin here. It is very well known that uncertainty about the SCC is huge. Downing *et al*.'s (2005) review, commissioned by DEFRA, provides a thorough analysis and estimates that the range of uncertainty is at least three orders of magnitude, from £0 per tonne of carbon to £1000/tC (about £270/tCO_2). The sources of this uncertainty are broadly threefold. First, there is uncertainty about how the climate will change and what impacts these changes will have in particular 'sectors' of the economy and society. Second, notwithstanding these uncertainties, there are differences between studies in their coverage of climatic changes (e.g. whether or not they attempt to quantify the impacts of extreme weather events, or catastrophic changes to the climate system) and the 'sectors' experiencing impacts (e.g.

whether or not they attempt to quantify impacts on human health). Third, different studies make different judgements on the (normative) decision variables determining social welfare, notably η and δ above.

The DEFRA paper proposes to use the Stern Review's estimate of the SCC on a path to stabilise greenhouse gas emissions at 550 ppm CO_2e. After various adjustments, this is £25/tCO_2e (2007 prices). In so doing, some of the above difficulties can be tackled. For one, the Stern Review's estimate is based on PAGE2002, which has been specially designed to summarise scientific and economic uncertainty about climate change (see Hope, 2006a). For a given set of choices about the model's decision variables, PAGE2002 has been shown to produce a central estimate close to the mean of a range of estimates produced by many other studies (cf. Hope, 2006a with Tol, 2005). Hence the concerns one might raise about choosing a single model as the basis for the SCC are somewhat allayed. For another, the Stern Review's estimate reflects choices on the normative decision variables that are arguably consistent with the UK government's overall policy on emission reductions. That is not to deny these choices are contentious; simply to observe that they are at least consistent with each other.

Nevertheless, significant uncertainties remain. Downing *et al*. (2005) were instrumental in highlighting that no integrated assessment model has comprehensive coverage of all of the impacts of climate change considered possible. For example, none explicitly take into account so-called 'socially contingent' impacts, which are large-scale, 'second-round' socio-economic responses to climate change like conflict and migration. More generally, PAGE2002 is limited in its capacity to reflect uncertainty by limitations in the underlying literatures. In many cases, the probability distributions that are estimated for PAGE2002's parameters are based on a range of underlying studies, which themselves only give 'best guesses'. As such, PAGE2002 can encapsulate uncertainty between the best guesses of other models, but it is unlikely to adequately capture uncertainty within these models themselves.

We can say that there is much these models omit, but on the other hand it is not immediately obvious whether PAGE2002 underestimates the impacts of climate change in the long run. This is because the uncertainty in its damage functions – i.e. describing the relationships between climate change, indexed by changes in mean temperature, and damages in terms of income losses – is very large, and the forecast impacts of climate change in the next century can be very small or very large. This is not a problem of omitted impacts as such. Rather it is a problem of a lack of validation. I conclude that we should continue to attach very little confidence to estimates of the SCC.

We are also very uncertain about the marginal abatement cost of carbon (MAC). We are uncertain about the cost of emission reductions, because we cannot predict with certainty what combination of mitigation techniques and technologies will ultimately be used and where, and how much they will cost when they are used. However, we have far more information today about the costs of these techniques and technologies than we do about the consequences of decades' more warming, globally. Loosely speaking, the comparison runs like this: while business-as-usual climate change could well take us far beyond the realm of human experience *within* the atmospheric lifetime of a tonne of carbon dioxide emitted today, we already have a feasible set of mitigation techniques at our disposal today, sufficient to stabilise greenhouse gas emissions at 550 ppm CO_2e, and we at least have fairly good information about what these techniques cost today. For these reasons, estimates of the MAC have been found to differ by about *one* order of magnitude (Watkiss *et al*., 2005) at most, roughly two orders of magnitude *less* than the uncertainty around the SCC. To provide more confidence in the SPC used in economic appraisal, I believe there is a role for estimates of the MAC. It would be unwise to replace the SCC with such estimates, but they can complement each other.

The shadow price of carbon and national decision-making

The SPC is a measure of the change in social welfare resulting from a marginal change in greenhouse gas emissions. In order to be used in a cost-benefit analysis, the SPC needs to be comparable with a host of other changes in social welfare, which would result from a particular policy or project. Since most of these are usually expressed in terms of changes in consumption, it is necessary to normalise the SPC to consumption as well.

While it is clear that, for comparability, the SCC should be expressed in relation to per-capita consumption at the time when the marginal tonne is emitted, the choice of to which nation or region it is normalised is not as straightforward as first appears (Anthoff *et al*., 2006; Anthoff and Tol, 2007; Newbery, 2006). In most of the previous literature, the SCC is estimated as the sum of global costs and normalised to global mean consumption per capita, with or without 'equity' weighting the costs in different regions depending on their income levels. This would essentially be the approach taken by a global planner and may, under certain circumstances, be the solution that would obtain if the countries of the world cooperated on climate policy. Under a set of very restrictive assumptions, it might also be the world price of carbon (e.g. the globally harmonised tax rate, or the price of a tradable permit in a cap-and-trade system with global reach).

But it is not immediately obvious that this would be the approach taken by the UK planner. His/her numéraire is UK consumption per capita, which is much higher than global mean consumption per capita. This would increase the SCC significantly. On the other hand, the UK planner might weight the impacts of climate change in other countries lower than the impacts in the UK. This would reduce the SCC. Moreover, the SCC, normalised to global mean consumption per capita, cannot be compared with the MAC, normalised to UK consumption per capita, although these comparisons have been made in the past (e.g. in Watkiss *et al*., 2005).

There is a clear need for more research on this issue. Newbery (2006) identifies the problem, but, like me, is unsure of the solution. Anthoff *et al*. (2006) and Anthoff and Tol (2007) conduct some preliminary analysis and demonstrate that, especially for wealthy nations like the UK, the ‘national’ SCC can be very different to the ‘global’ SCC that has been the focus of the literature until now.

The social cost of other greenhouse gases

A minor concern with the DEFRA paper is with the method put forward for estimating the shadow value of emissions of other greenhouse gases. This is based on so-called “global warming potentials” (GWPs), which are a measure of how much a given mass of greenhouse gas contributes to warming. GWPs are a relative measure, expressed in relation to carbon dioxide, which has a GWP of 1. They are also highly dependent on the time horizon in question, in large part because one of the chief determinants of a GWP is the decay rate of the gas in the atmosphere. Thus the GWP of methane falls over time, because, although it has a higher radiative efficiency than carbon dioxide, it resides in the atmosphere for a shorter time.

DEFRA proposes a simple method for estimating the shadow price of greenhouse gases other than carbon dioxide, whereby the SPC is multiplied by the 100-year GWP of the gas in question. The difficulty is that the properties of GWPs can make them a poor approximation of directly estimating the marginal damage cost of these other gases. Hope (2006b) demonstrates this for sulphur hexafluoride. His direct estimate of the marginal damage cost of sulphur hexafluoride is $200,000/t (year 2000 prices), which is 40,000 times higher than his estimate for carbon dioxide. However, the 100-year GWP of sulphur hexafluoride, reported in the DEFRA paper is only 23,900. Thus the shadow price of sulphur hexafluoride would be significantly underestimated using the indirect, GWP method. One of the principal reasons for this is that the GWP method does not allow for the fact that climate-change damages caused earlier by a more ‘potent’ greenhouse gas should be discounted less.

Of course, the difficulty facing any planner attempting to estimate the shadow price of greenhouse gases other than carbon dioxide is the paucity of information. Most research on marginal damage costs has focused on carbon dioxide. Therefore, for many greenhouse gases, there will be no alternative to approximating the shadow price using GWPs. However, where available, evidence from direct estimates should be used.

References

Anthoff, D., C. Hepburn and R. S. J. Tol (2006). Equity weighting and the marginal damage costs of climate change. Working Paper FNU-121. Hamburg, Hamburg University and Centre for Marine and Atmospheric Science.

Anthoff, D. and R. S. J. Tol (2007). On intergenerational equity weights and national decision making on climate change. Working Paper FNU-127. Hamburg, Hamburg University and Centre for Marine and Atmospheric Science.

Clarkson, R. and K. Deyes (2002). Estimating the social cost of carbon emissions. Government Economic Service Working Paper 140. London, HM Treasury.

Dietz, S., A. Bowen, C. Hepburn, C. Hope, N. Patmore and N. Stern (2006). On discounting non-marginal policy decisions and cost-benefit analysis of climate-change policy. International Society for Ecological Economics Ninth Biennial Conference, Delhi, 15-19 December.

Downing, T. E., D. Anthoff, B. Butterfield, M. Ceronsky, M. Grubb, J. Guo, C. Hepburn, C. Hope, A. Hunt, A. Li, A. Markandya, S. Moss, A. Nyong, R. S. J. Tol and P. Watkiss (2005). Scoping Uncertainty in the Social Cost of Carbon. London, DEFRA.

Drèze, J. and N. Stern (1990). "Policy reform, shadow prices, and market prices." Journal of Public Economics **42**: 1-45.

Hope, C. (2005). The economics of climate change. House of Lords Select Committee on Economic Affairs, Volume II: evidence. London, The Stationery Office.

Hope, C. (2006a). "The marginal impacts of CO2, CH4 and SF6 emissions." Climate Policy **6**(5): 537-544.

Hope, C. (2006b). "The marginal impact of CO2 from PAGE2002: an integrated assessment model incorporating the IPCC's five reasons for concern." Integrated Assessment **6**(1): 19-56.

Maddison, D. J. (1994). Economics and the Environment: the Shadow Price of Greenhouse Gases and Aerosols. Surrey Energy Economics Discussion Papers 76. Guildford, University of Surrey.

Nakicenovic, N. and R. Swart, Eds. (2000). Special Report on Emissions Scenarios: a Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge, Cambridge University Press.

Newbery, D. (2006). Extract from chapter 'Calculating the social cost of carbon'. Cambridge, University of Cambridge.

Pearce, D. W. (2005). The social cost of carbon. Climate-change Policy. D. Helm. Oxford, Oxford University Press**:** 99-133.

Sen, A. K. (1972). "Control areas and accounting prices: an approach to economic evaluation." Economic Journal **82**(325): 486-501.

Stern, N. (2007). The Economics of Climate Change: The Stern Review. Cambridge, UK, Cambridge University Press.

Tol, R. S. J. (2005). "The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties." Energy Policy **33**(16): 2064-2074.

Tol, R. S. J. and G. W. Yohe (2006). "A review of the Stern Review." World Economics **7**(4): 233-250.

Watkiss, P., D. Anthoff, T. E. Downing, C. Hepburn, C. Hope, A. Hunt and R. S. J. Tol (2005). The Social Costs of Carbon (SCC) Review – Methodological Approaches for Using SCC Estimates in Policy Assessment, AEA Technology Environment.