Cumulative Carbon Emissions and Climate Change:

Has the Economics of Climate Policies Lost Contact with the Physics?

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Summary

Carbon dioxide (CO_2) emissions are essentially cumulative. The thesis of this paper is that much economic analysis and policy making in relation to the mitigation of CO_2 emissions has failed to reflect fully this essential element of the science. In particular the cumulative and irreversible nature of CO_2 implies that a significantly heavier weight should attach to current as opposed to future emissions. This is in major contrast to current application of market-based approaches to limiting carbon emissions. Application of a progressive tightening of "carbon caps" – limits on total CO_2 emissions - has tended to deliver a very different message on the relative importance of present and future emissions, with the price of current emissions being very low but with a prospect of rapid rises in the future. This inconsistency in time profiles, between a focus on costs or externalities – the social cost of carbon (SCC), and the market price outcome from an emissions cap approach, has the potential to create major distortions in policy and is likely to be seriously sub-optimal. Similar criticisms could be levelled at policies or climate negotiations which tend to focus on individual year targets rather than cumulative emissions. Policy making needs to redress this imbalance. Recognition of the cumulative nature of CO_2 should strengthen the case for urgency and also lead to more recognition of the option value of early action on emissions.

1. Introduction: The Cumulative Nature of CO_2 Emissions

There are two widely accepted hypotheses about the effect of man- made (anthropogenic) carbon dioxide emissions, which are fundamental to examination of the climate consequences of emissions and of their economic and environmental costs, and hence to any development of policy to limit or mitigate those costs.

The first is the well understood phenomenon of greenhouse gases (GHG) as agents of radiative forcing (the greenhouse effect). It is the level of their concentration in the atmosphere, *not* the current level of emissions, which determines the extent of the warming effect from their presence in the atmosphere. In other words it is the cumulative effect of past emissions from all sources that matters – the stock of CO_2 rather than the flow. Of course, in examining the effect in relation to any assumed climate equilibrium, the climatic impact of any given increase in the stock in a given year is not confined to that year and may persist over many years, through thermal inertia and other consequences for the dynamics of climatic systems; but the essential point is that it is the cumulative concentration of GHG that drives future climate disturbance. This is well understood and accepted as one of the major building blocks for any investigation of the climate effects of emissions.

The second hypothesis is that man-made emissions of the most important of these gases, carbon dioxide (CO_2), should be regarded, for the purpose of evaluating climate impact, as almost wholly cumulative, in that very little of any incremental emissions of CO_2 are re-absorbed. This hypothesis needs to be stated much more carefully, not least because it is a central feature of the claim that anthropogenic emissions do indeed give rise to a high risk of global warming, and is central to any argument for early action.

At one level this hypothesis too is a simple matter of fact: in the laboratory CO_2 does not react or break down in air, and does not have the equivalent of a radioactive half-life. In that sense its presence in air is purely cumulative. However we are much less interested in the laboratory behaviour of CO_2 than in what happens within the context of natural carbon cycles which involve very large natural transfers of CO_2 to and from the atmosphere every year, the largest being transfers to/from plant life and to/from the oceans. Our concern should be with the cumulative impact of man-made CO_2 emissions on future CO_2 concentration levels, within this context.

The volumes of transfers each year, in both directions, between the atmosphere and oceanic and terrestrial sinks, are much larger than the current levels of man-made emissions. However if anthropogenic emissions have no effect on the exchanges in this “natural” carbon cycle, then they will be purely cumulative; although annual emissions may be small, the cumulative amount over decades will be large. If on the other hand the injection of this additional CO_2 does affect the carbon cycles, through climatic or other effects which increase or reduce the carbon cycle exchanges, then the impact of man-made emissions may be less than or more than wholly cumulative. This question is central to all attempts at estimating the overall impact of man-made emissions on climate through, for example, climate models. If CO_2 emissions were not essentially cumulative then it would be more difficult to argue that their climate change consequences were irreversible and it is much less likely that climate models would substantiate the arguments for action to limit anthropogenic emissions.

This paper is not intended to address or comment on this question as a matter of science. However we can record, simply as an observation, that the current underpinnings of the climate science consensus do treat man-made emissions as essentially cumulative[1]. Conventional assumptions appear to put net re-absorption at the very low level of 1% pa, but it is recognised that interference with natural carbon cycles might reduce re-absorption to much lower rates or, in worst case scenarios, create a positive feedback of negative re-absorption. There are studies [2] that "... have suggested that the terrestrial biosphere will become a less effective net sink of carbon, and may even become a source.". In other words an incremental tonne of CO_2 emitted might in this case result in more than one additional tonne of CO_2 in the atmosphere. It is therefore legitimate, if we treat emissions policy as a response to a real and serious problem, and from a perspective that takes the mainstream science as its fundamental justification, to regard CO_2 as essentially cumulative.

One important corollary of this second hypothesis, on the essentially cumulative nature of man-made CO_2, is that the damage caused by present emissions, those for (say) this year, will tend to be greater than that from future emissions, e.g., those in five years time. This is easily demonstrated[3] by comparison of year after year costs of a given volume of CO_2 that persists; the damage caused by its presence in each year is independent of the year in which it was emitted. Recognition of this corollary has been confirmed explicitly in at least one integrated assessment modelling exercise, using the PAGE model, and described in a 2005 AEA Technology report.[4] The PAGE model provided the basis for the most recent UK official position[5] on the social cost of carbon, set out by DEFRA. It was given particular prominence in the economic modelling chosen to conduct analysis within the Stern review[6], and has been described by Hope[7]. This modelling shows a time profile for the SCC, discounted back to the common base year 2000, falling by about 1% pa. Appendix 3 of that report shows an SCC value falling from £ 61 per tonne in 2010 to £ 55 per tonne in 2020.

The authors of the AEA report were however also at pains to point out that this result does ***not hold*** for another important greenhouse gas – methane. The authors state this result for methane as follows:

> *"Indeed, the SC discounted to 2000 actually rises over time. This is because of the short atmospheric lifetime of methane; any methane emitted today will have disappeared from the atmosphere before the most severe climate change impacts start. This implies that given a*

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[1] Some further discussion on this point is provided in the Annex to this paper.

[2] *Climate-carbon cycle feedbacks under stabilization: uncertainty and observational constraints.* Jones, C.D., P.M. Cox and C. Huntingford (2006). Tellus Series B. Chemical and Physical Meteorology. 22 September 2006.

[3] A simple mathematical presentation of the argument is given in the Annex to this paper.

[4] *The Social Costs of Carbon (SCC) Review –Methodological Approaches for Using SCC Estimates in Policy. Assessment. Final Report.* Paul Watkiss with contributions from David Anthoff, Tom Downing, Cameron Hepburn, Chris Hope, Alistair Hunt, and Richard Tol. AEA Technology Environment UK. December 2005.

[5] *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.* December 2007. Economics Group, DEFRA.

[6] *Stern Review on the Economics of Climate Change*. HM Treasury. October 2006. Chapter 6.

[7] *The marginal impacts of CO2, CH4 and SF6 emissions*, C Hope, Judge Institute of Management Research Paper No.2003/10, Cambridge, UK, University of Cambridge, Judge Institute of Management.

choice today between emitting 1 tonne of methane now, or at some time up to 60 years in the future, we should opt to emit it now."

In other words there is a very clear contrast with the cumulative nature of CO_2.

Our corollary on the additional weight attaching to early emissions, although supported by the report's observations on the shape of the time profiles for the social cost of CO_2 and methane, does not depend on any particular model. It is essentially no more than a simple logical consequence of the cumulative nature of CO_2. As such, its validity is far less sensitive than is the absolute level of the SCC to the more controversial assumptions and modelling that underpin the general cost-benefit framework of the Stern Review.

We can therefore state that, given the greater damage done by early emissions, it makes sense to give them a greater weight. Implicitly this reinforces the economic arguments for urgency in tackling emissions as a critical element of climate policy. This can be contrasted with a number of observations on current policies, first if these place excessive focus on single year targets, and second where they rely on market mechanisms which currently deliver a very different set of expectations on carbon pricing.

2. Social Cost versus Emissions Cap and Market Price of Carbon Approaches

There are two main approaches to use of market and price mechanisms to limit emissions:

- to price or tax emissions to fully reflect their social cost, a "Pigovian"[8] approach, to which the above observations are most obviously relevant , ***or***
- to set an emissions limit, reflecting an agreed combination of "safety" and practicality, and allow markets to set a price on the basis of trading emissions within that limit or cap – "cap and trade".

Although the alternatives of fixing price and fixing quantity can sometimes be treated as if they are or ought to be equivalent under certain well-specified conditions, this is clearly not the case in the context of the complex institutional structures and political, economic and technical factors that pertain to current and recent policy making on EU and UK emissions. For practical and political reasons, governments, where they are willing to address the problem, have favoured the second "cap and trade" approach, a choice for which the following considerations provide at least a partial explanation:

- difficulty in attaching any precision to social costs, estimated as economic consequences, that depend on so many economic and policy unknowns of a global nature, stretching into a relatively remote future; this would be so even if there were general consensus that the

[8] Pigovian taxes are named after Arthur Pigou, a Cambridge economist best known for his development of ideas on externalities and the use of taxes and subsidies to deal with them.

negative consequences lie in a range from the substantial to the catastrophic; estimates of the "allowed limit" of CO_2 concentration, required by the second approach, are also subject to uncertainty and controversy, but the uncertainty is of a lower order of magnitude.

- attempts to set policies (for emission reduction and the limitation or mitigation of climate change) within a conventional cost benefit analysis are further handicapped by profound disagreements among economists over the rate of discount to be applied to future costs; this reflects both the limitations of conventional capital theory and inability to reach consensus on the "moral" issues of inter-generational equity; this apparently simple issue, the choice of discount rate, has a dominating effect on any measure of the social cost of consequences that may be spread over many decades or several generations.

- a consensus that, even though there may be a very high level of future social cost, imposition of a cost-reflecting tax would tend to imply large immediate price impacts on consumers, on particular sectors of the economy, and on income distribution, which national economies and their associated political processes are not well equipped to handle or to offset.

- a "cap and trade" approach, combined with regulatory or other interventions, will, it is hoped, deliver the desired policy outcome, but with a lower impact on consumer prices; it is implicitly assumed that a much more gradual approach, with very limited initial price impact, and lower long run price impacts, might be sufficient to deliver low carbon investment, and hence be as effective but more palatable than a Pigovian tax. It is also true that many abatement policies, whether in terms of energy production choices or in the regulation of energy demand, have costs that are low in relation to the presumed social costs of CO_2 emission.

- a "cap and trade" approach can to some extent be seen as a natural concomitant of target based approaches to emissions policy, especially if targets are expressed predominantly in terms of actual emissions in a given year (the flow rather than the stock)

The pattern of prices that is now emerging from actual application of the "cap and trade" approach is very different from what would be expected from the social cost or "Pigovian" approach. To illustrate this, the traded price of CO_2 permits has slumped to around €10 a tonne during the current recession, while discussions around proposed carbon floor prices indicate levels of at least €35 - €50 a tonne as the basis for promoting low carbon power generation. The carbon price floor announced[9] in a recent UK Budget begins at around £15.70/tCO_2 in 2013 and follows a straight line to £30/tCO_2 in 2020, rising to £70/tCO_2 in 2030 (real 2009 prices). In other words we might assume that this policy approach is now pointing towards a steeply rising carbon price, and that prices rise as caps are progressively tightened. By contrast the most recent 2007 DECC estimates of the SCC, quoted above, would put the cost of current year emissions at around £60 a tonne, falling by about 1% pa when comparisons are discounted to a common base year, and rising only slowly even when

[9] Planning our electric future: A White Paper for secure, affordable and low carbon electricity. CM 8099. July 2011.

estimated as a cost discounted[10] only to the year of emission. In other words there is a major divergence not just in the current level of the CO_2 cost/price, but also in the time profile.

Of course the low level of carbon prices can, with some justification, be attributed to failure to implement sufficiently stringent limits on CO_2 within the EU ETS. While the actual pattern now anticipated, of a rising market price for carbon as emission controls progressively tighten, may seem to make some intuitive sense, in reality it reflects a policy failure, and leads, as will be shown below, to some paradoxical implications.

One inference that we might draw from this comparison is that, had policy makers compared the carbon price outcome and market expectations under the early cap and trade arrangements with the time profile that derives from a logical interpretation of the science of cumulative CO_2, it would have been apparent at an earlier stage that the cap and trade approach, in its current form and with its current limits, is failing to address the problem at which it is aimed.

3. Paradoxical Consequences for Emissions Policies

To demonstrate why this matters for emissions policies and targets, it is useful to consider the following simple paradox of how a policy failure can be derived from contemporary targets and the assumption of a rising carbon price.

Suppose I have a large store containing thousands of tonnes of CO_2, held under pressure in large corroding metal vessels. Technical experts have advised me that there is no means of permanently sealing the vessels, other than at prohibitive cost, but that I can with only modest expense treat the seals of the vessels in a way that will prolong their expected life from 6 months to 20 or 30 years, at which point there will be a slow leakage into the atmosphere, perhaps over a 10 year period. What should I do, given an objective of minimising adverse climate impact?

Answer. ***Working from a measure or price signal that suggests later emissions are significantly more damaging, such as a rising carbon price, the answer seems obvious. We should be prepared to spend money not on reinforcing the vessels, but on breaking them open immediately, since the social cost will be significantly higher in 5 years time and even more so in 30 years time. Moreover immediate release will additionally make it easier to meet annual emissions targets for future years.***

This is clearly absurd if limiting the CO_2 stock is the real target and if CO_2 emissions are essentially cumulative. Immediate release, using PAGE modelling numbers merely to illustrate the point, should be assumed to be some 20-30 % more damaging.

Moreover simple reliance on a PAGE or similar calculus ignores the possibility that a novel low cost technical solution will be developed for the problem of sealing the corroding tanks. There is

[10] A discount rate of 3.5 % is implicit in the DEFRA commissioned work. Use of higher rates would tend to produce sharper rises, when SCC is calculated at the year of emission, and to reduce the SCC at a common base year, but not to alter the profile of an SCC that declines slowly over time.

therefore an additional option value which attaches to not releasing the CO_2, but this value is not captured in the simple SCC analysis.

This is obviously a hypothetical construct, although in a future that includes carbon capture it seems quite credible that closely analogous situations involving storage would arise. But it serves very directly and simply as a parable to illustrate how ignoring the basics of CO_2 science could lead to perverse policy outcomes.

We now move on to a few of the policy implications of recognising explicitly that it is cumulative CO_2 not annual emissions that is the issue. These are discussed briefly in the next four sections:

- Implications for global and national target setting.
- The importance of price signals in relation to policy, especially where there is a heavy reliance on market mechanisms to deliver required policy outcomes.
- Maintaining urgency in climate policy when confronting low market prices for carbon emissions.
- The option value of early action.

4. Setting Global Targets and National Policies

Economists generally assume, correctly, that if any form of regulation or policy targets the wrong indicator, for example by making the volume of inputs rather than the value of outputs into a business growth objective, then the results are likely to be disappointing if not perverse. This is a truism in critiques of Soviet planning (quantity targets unrelated to value) and in the conduct of monetary policy (measures of money supply which may be indicators but cannot be controls).

A first requirement of CO_2 targets therefore is that they should align with the objective. This should be to minimise or at least limit cumulative emissions, not to achieve a particular level by a given date. Targets for annual emissions by 2050 may be useful indicators, as "headline" statements of what is required but they should not obscure the primary objective, reinforced by Stern, of keeping ***cumulative*** emissions within "safe" limits. Larger early reductions, if they can be achieved and sustained, are disproportionately beneficial in reducing cumulative emissions, and hence in delaying adverse climate impacts. As an immediate consequence they have a large and additional option value in "buying time" both to allow a wider range of CO_2 mitigation technologies to be developed, and to allow more time for adaptation to any climate change consequences that cannot be avoided.

In principle this is an obvious point but the scale of its importance is surprising. To illustrate the point we consider an 80% reduction over a 40 year period[11] (by 2050) which corresponds to a proportionately constant 3.85% pa reduction over the period. If we hypothesise alternative paths that are front-end or back-end loaded, perhaps 1.5 to 2% higher or lower initially for the first 20 years,

[11] This number is chosen, purely as an illustration, to correspond to the actual UK target, but the implicit context is global.

and then at a constant rate that gives the same final year emissions, we note some dramatic differences.

Thus even compared to a constant rate of reduction, front-end loading delivers a contribution to cumulative CO_2 that is more than 15% lower and corresponds to about 15 years of emissions at the achieved 2050 annual rate. One interpretation of this arithmetic would be to argue that some climate milestones, in terms of increased concentration levels, would be reached 15 years later under front-end loading, implying substantially more time to initiate additional measures including adaptation. Back-end loading has correspondingly negative consequences of similar magnitude, implying an immense difference in outcomes if one compares back-end directly with front-end loading.

The point of the above is simply to demonstrate that there are very large and important differences between different time profiles for emissions reduction, which are not captured at all by final year targets, and correspondingly may not be captured adequately even by intermediate medium term targets. Putting a valuation on these differences in CO_2 concentration outcomes leads to a further accentuation of the differences, and the benefit of front-end loading, if one uses measures of the SCC that capture correctly the higher value of early emission reduction.

A particularly important general conclusion from these observations is that early action has a potentially very large "option value" which is implicit in buying time and expanding the range of future policy options to deal with climate issues, whether in mitigation or adaptation.

International negotiation: National targets

The undeniable primacy of cumulative emissions as the right measure of performance in abating CO_2 concentration implies that a rational approach to the design of an international regime and associated market mechanisms must also be based on cumulative emissions from a baseline, with carryover of emission rights/savings between time periods, and certainly not on rigid annual numbers.

Essentially this point, and that made above, was argued by Myles Allen, then Head of Climate Dynamics, Department of Physics, University of Oxford, both in a recent interview with the FT[12] and in a recent April 2009 paper[13] in Nature.

> *"Allen believes the current approach to tackling climate change is ill-conceived. His latest paper, published earlier this year* [2009] *in Nature, argues we should be looking at the total amount of carbon that humankind emits, not the rate at which we do so – the measure the negotiators in Copenhagen will be focusing on.*
>
> *He shows me a graph with three different curves representing the same amount of carbon being emitted over different timescales. "Temperature response is identical," he says. "It's much easier to frame the problem if you say 'what's the total amount of carbon we can afford to inject into the atmosphere' rather than what concentration should we be aiming*

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[12] http://www.ft.com/cms/s/2/f1d9f856-d4ad-11de-a935-00144feabdc0.html#ixzz1HFgW1zay provides a link to the relevant FT feature article.

[13] http://www.nature.com/climate/2009/0905/full/climate.2009.38.html. *The Exit Strategy*. Myles Allen, David Frame, Katja Frieler, William Hare, Chris Huntingford, Chris Jones, Reto Knutti, Jason Lowe, Malte Meinshausen, Nicolai Meinshausen & Sarah Raper. Published online: 30 April 2009

for." Yet because of the way the Rio Earth summit and Kyoto Protocol configured the problem, negotiations at Copenhagen are heading in the wrong direction."

These are the considerations that should permeate into the structure of negotiations over how any given burden of emissions reduction should be shared. Their importance is accentuated and reinforced by issues of monitoring and enforceability. There are of course many other considerations that impact on real world negotiation, but it is not necessary to detail these in order to note that issues of fairness, rational incentive structures, and monitoring, all point to the need to base global solutions, in principle at least, on approaches that stress cumulative emissions rather than arbitrary single year targets.

There is of course a powerful case in principle for a single global market mechanism, whether based on a carbon price or tax, or a cumulative cap. However this raises many questions of measurement, monitoring and enforcement, and it is even harder to envisage a comprehensive market, sufficient to replace negotiated targets, themselves as yet not much more than an aspiration, within any reasonable timescale. In an imperfect "second best" world in which individual countries or blocs such as the EU engage in negotiations with each other, a rational approach to national or regional performance measures should be expected to build on a principle of cumulative targets.

Without a cumulative measure, nations or blocs that achieved early and permanent reductions would rationally feel aggrieved if they were not rewarded for their actual contribution. There would also be more opportunities for free-riding, with some countries knowingly accepting over ambitious but distant and back-end loaded targets. Effective monitoring of performance would also be more difficult if based only on a small number of target years.

It follows that aligning national or bloc targets to be consistent with the shape and structure of an agreed cumulative aggregate number would be an essential part of a global strategy based on seeking to contain atmospheric concentration of CO_2. In the UK at least this is recognised to some degree in the use of intermediate targets and period-based carbon budgets which allow implicitly for some movement of emissions between calendar years.

5. Getting the Right Price Signals

The market approach, unsurprisingly since it is the basis for the EU ETS, dominates most discussion of investment and other commercial decisions in the energy sector, while the influence of the SCC approach, such as it is, is confined to issues of policy concerning the public sector, regulation and other non-market interventions such as innovation policy. One justification for this is the belief that a "market price" approach, subject to suitable reforms of energy markets, will in the long run deliver the necessary levels of new low carbon investment, particularly in the crucially important power sector. This investment would then have been achieved at lower cost to final consumers and perhaps with less risk of windfall profits to existing or low cost producers. These are persuasive but not conclusive arguments in an investment context, since there will inevitably be some investment decisions which will change as a result of a different view of the time profile of CO_2 prices.

However there are many other commercial decisions within the energy sector, of an operational rather than a long lead time investment nature, which would be influenced by the much tougher signals given by a carbon price that reflected a higher and front-end loaded SCC, as compared to the current reality of a low but possibly rising market price of CO_2 emissions. Given that there are serious discrepancies between the two approaches the there is at least a prima facie argument for addressing this difference as a market failure.

Apart from the obvious influence of a higher SCC, in reinforcing the case for regulatory measures to secure "easy" gains for energy efficiency and conservation measures, the "low hanging fruit", there are at least two other very obvious examples where the weight attaching to relative carbon emissions, and also their timing, might be expected to have a significant impact, not just on investment but on operational decisions.

A first is in the context of fuel substitution in the power sector. Recognition of the value of early reductions in CO_2 would encourage earlier rather than later substitution of gas for coal in power generation. In global terms, this is a significant short term source of CO_2 reduction, often involving little or no additional investment. Although this is in part a purely commercial decision for generators responding to visible price signals, it is also sometimes seen as a matter for public policy when other factors such as security and diversity of supply are involved. Moreover fuel substitution is a relatively low cost CO_2 abatement option, often with relatively modest investment costs.

A second is in the context of carbon capture and storage. The balance between profiles involving early or later emissions is potentially a major consideration in relation to a number of investment, design and operating choices both for generating plant and for the storage infrastructure. Obvious examples can be constructed in relation to choice between technologies or modes of operation involving different rates of CO_2 capture, and in relation to the security of storage. If this is so, then there should be a clear benefit to those choices being informed by price and cost signals that reflect the physical realities of CO_2 emissions.

A third rather more hypothetical example is the ''green paradox'' postulated by Hans-Werner Sinn[14], who suggests that increasing resource taxes might accelerate global warming. His argument is that resource owners will increase near-term extraction in fear of higher future taxation. This might be a realistic concern in relation to a sharply rising market price of CO_2. Clearly it would not be the case with a well-defined SCC based charge that had a declining profile.

[14] *Public Policies Against Global Warming,* Hans–Werner Sinn, NBER WORKING PAPER SERIES 13454, September 2007

6. Presentation to Reflect Urgency

The observation that market-determined carbon prices (within the EU ETS) are low, and predictions that the market price of carbon will rise, reinforce the widespread perception that the problems of climate change, even if serious, are relatively remote, and therefore that action or expenditure to mitigate it can or indeed should be delayed.

This erroneous impression is reinforced in a number of policy papers, and is evidenced by a number of the quotes below. One explanation is that projections for the market price of carbon have more prominence than estimates of the SCC. A second is that the truth, of a higher cost of near term emissions, can appear counter-intuitive. Some examples illustrate the widespread nature of the misconception.

UK Government Department - DEFRA

The first is the 2007 DEFRA paper, referred to earlier, which was intended to deal specifically with the issue of the social cost of carbon in the context of policy making and public sector decisions. The numbers were derived from the AEA Review referenced above, with a falling profile when a common base year is used. However the paper presents instead a time profile for the SCC based on costs discounted only to year of emission; which rises over time, by 2.0% pa. It is explained as follows:

- *As time goes on, the damage comes closer, and is discounted less heavily; so its present value rises, increasing the SCC.*

This explanation is correctly describing the fact that the social cost of carbon, when discounted back to the year of emission, is rising. When a common base year is used, i.e., like is compared with like, and for any discount rate above 2% (the rate used was 3.5%), the SCC falls over time. But at least this statement is correct in its own terms, even if some readers might find it misleading.

Unfortunately the report seeks a further justification of a rising profile.

- *The concentration of carbon in the atmosphere is rising towards its long-run stabilisation level, and expected climate-change damages accelerate with higher concentrations.* ***An extra unit of carbon will do more damage at the margin the later it is emitted because, even with a plausible concentration goal, it will be in the atmosphere while concentrations are higher*** *and higher concentrations mean larger climate-change impacts at the margin (as damage is a function of the cumulated stock); this too increases the SCC.* ***Additionally, as incomes grow, so the monetary value of damage is likely to grow, owing to an associated higher willingness to pay to avoid warming damage.***

Both the explanations highlighted by this author in the second bullet are clearly wrong, for the reasons outlined earlier. They ignore the persistent effect of earlier emissions. Incremental emissions in 2011 are still around in 2020 (ignoring for the moment the very modest re-absorption) and causing the same amount of damage as incremental emissions made in 2020. However this demonstrates very well the link between a failure to focus on the fundamental issue of cumulative effect and the perception that the costs imposed by particular emissions will not get dramatically larger until concentration has increased.

Better Regulation Commission

The second example is a report from the Better Regulation Commission[15], in a response to the Stern Review, which falls into precisely the same trap.

- *As carbon concentration in the atmosphere rises towards the long-term level implied by the stabilisation target, the damage at the margin caused by further emissions – the social cost of carbon – will inevitably increase. This means that the appropriate price of carbon will rise over time. This is likely to be an important feature of the regulatory framework that needs to be put in place to combat climate change. People in both the public and the private sector will need to take a view on the likely future path of the price of carbon when taking investment decisions regarding long-lived capital.*

This displays exactly the same logical error. The "money of the day" cost at the date of emission will rise, but not the actual damage, when like is compared to like.

Academic papers

A third example is from one of the AEA report authors.

- *Figure 3 shows how the PAGE estimates for the SCC vary with the date that the carbon dioxide is emitted. The values increase by about 2.4% per year; by 2060 the mean estimate has risen to \$265/tC (\$72/t CO_2). They increase for the simple reason that as we get closer to the time when we expect the most severe impacts of climate change to occur, then the extra impact from putting another tonne into the atmosphere gets higher* [16]

In this case the authors understand the issue. Chris Hope first[17] drew my attention to the AEA Technology report as a source of SCC estimates, to the fact that DEFRA estimates were not quoted to a common base year, and to the contrast between CO_2 and methane from a timing and damages perspective. But the argument presented here is inaccurate, as in the two earlier examples. Without the necessary qualification that the numbers are not taken back to a common base year, this paragraph again gives a misleading impression, that the marginal impact of an extra tonne of CO_2 emissions does more damage when it occurs later rather than earlier, even though the earlier emission is still in the atmosphere.

[15] *Regulating to mitigate climate change – a response to the Stern Review,* Better Regulation Commission, February 2007

[16] *Calculating The Social Cost Of Carbon.* Chris Hope, Judge Business School, University of Cambridge and David Newbery, Faculty of Economics, University of Cambridge, May 2006.

[17] private communication.

Another example is from a paper[18] by Hoel, engaging with the "green paradox" referred to above.

- *In particular, the optimal carbon tax should at any time be equal to the discounted value of all future marginal climate costs caused by the present emission. At an early stage, when the optimal path of carbon in the atmosphere is rising, increasing marginal climate costs will imply a rise over time in the optimal carbon tax (see e.g. Hoel and Kverndokk,1996, for details). An obvious problem with implementing an optimal policy is that policy makers cannot commit to a rising carbon tax.*

The author's concern, with the difficulty of commitment to a rising carbon tax, is possibly easier to resolve if one accepts that the actual cost is falling rather than rising on a common year of measurement basis.

In other words the social cost of carbon is routinely and misleadingly described as rising slowly, omitting a fundamental feature of the analysis on which the estimates are based. Not surprisingly such observations, which are commonplace, will tend to suggest there is less immediacy on climate issues, and will tend to understate the gains from early action.

7. Option Values

Recent approaches to decision theory, in "real options theory" embody the principle that a positive value can attach to the deferring of a decision until more information is available. To summarise the approach[19], an investment decision can be treated as the exercising of an option. If an investment is irreversible (a sunk cost), then there is an opportunity cost attaching to an investment made now rather than waiting. The greater the uncertainty, the greater is the value of the firm's options to invest, and the greater is the incentive to keep those options open.

In the context of climate change policy it is often assumed that uncertainty implies that the most appropriate response is to postpone policy actions pending better information, in other words that an option value of delay attaches to doing nothing. However this is little more than a verbal sleight of hand. Large actual investments will be made within the alternative scenarios of policy action and policy inaction. One of the guiding principles of real options theory however is the idea that it is the feature of irreversibility that attaches a high cost to taking a particular course of action now, as opposed to waiting.

A consequence of the earlier analysis of the science consensus is that, in the context of potential responses to CO_2 and climate issues, it is the policy of inaction that results, through the cumulative effect of CO_2, in irreversibility, since it is inaction that results in the greater release of CO_2. This is illustrated very well by the example of the "leaking tank", where deferring release allows for the possible development of a permanent solution. It is also illustrated by the observation that front-end loading of emission reductions will postpone the CO_2 emission or climate milestones at which particular concentrations are reached and particular impacts occur, allowing more time to develop additional measures to mitigate or adapt. Hence one might assume a presumption in favour of early

[18] *Climate change and carbon tax expectations.*; Michael Hoel. February 2010. CESifo University of Oslo (Center for Economic Studies and Ifo Institute for Economic Research). CESifo Working Paper Series No. 2966

[19] *Investment under Uncertainty,* Dixit, A.K. and Pindyck, R.S. 1994. Princeton, NJ: Princeton University Press.

policy action as having a positive option value. This observation further increases the differential that should apply between early and later emissions reductions.

8. Conclusions

The analysis above has confirmed the cumulative nature of anthropogenic CO_2 as an integral element in the consensus science underpinning policies seeking to limit greenhouse gases and climate change. This carries the important corollary that, in principle, a heavier weight should attach to current and near term emissions than to emissions in 10, 20 or 30 years time.

This stands at variance with a number of features of current policy and comment, in particular:

- The inability to focus policy and negotiation on cumulative measures at a global level, a failure that has been highlighted by scientists but is not widely recognised.
- Inconsistency between the expected profile of "market determined" CO_2 prices and that of the profile of damage and the externalities of environmental and other costs associated with emissions.
- A misleading presentation of the basis for current emissions policy.
- Justification of policy inaction on the basis of a "wait and see" approach.

Early emissions are more damaging because emissions are cumulative and hence early emissions are around for longer; corresponding to this, early measures to reduce emissions are of more benefit than later measures. This should lead us to the following general conclusions:

- Cumulative emissions, i.e., stocks, are the proper focus of policy, not annual emissions (flows); this needs more explicit recognition in an international context.
- The profile of emissions reduction can have a very large impact on cumulative CO_2 at any given future date, with a consequential impact for the policy options that will then be available.
- Although many critical strategies to secure long term low carbon investment are based on a gradualist approach of increasing market prices, there are strong arguments for seeking to ensure that an SCC based approach needs to be reflected into policy choices relating to fuel substitution; inter alia this tends to reinforce the case for early substitution of gas for coal and might become very significant in relation to carbon capture and storage.
- Early savings not only have a higher beneficial impact; they also "buy time" and can be considered to have an additional and substantial option value; this contradicts the common argument that it is always delay, to gain further information, that has a positive option value. It is early action that delivers option value in the context of climate policy.

Annex: Interpreting the Science of CO_2 and Climate Impacts

In this annex we expand on two of the points already covered briefly in the main text. First we describe in a little more detail the phenomenon of re-absorption within the carbon cycle. Second a mathematical presentation shows that the cumulative nature of CO_2 implies a higher cost attaching to current emissions.

1. Examination of questions regarding re-absorption of CO_2 within the Carbon Cycle

CO_2 does not decay, react or break down in air, and does not have the equivalent of a radioactive half-life. Under laboratory conditions its introduction to an atmosphere might be described as purely cumulative. However we are much less interested in the laboratory behaviour of CO_2 than in the additive effect of ***incremental*** CO_2 emissions on future CO_2 concentration levels within the earth's atmosphere. This needs to take into account the actual re-absorption of CO_2 from the atmosphere into oceanic or terrestrial sinks.

This subject is discussed in some depth in Chapter 8 of the Stern Review.[20]

> *"Weakening of Natural Land-Carbon Sinks: Initially, higher levels of carbon dioxide in the atmosphere will act as a fertiliser for plants, increasing forest growth and the amount of carbon absorbed by the land. A warmer climate will increasingly offset this effect through an increase in plant and soil respiration (increasing release of carbon from the land). Recent modelling suggests that net absorption may initially increase because of the carbon fertilisation effects.... But, by the end of this century it will reduce significantly as a result of increased respiration and limits to plant growth (nutrient and water availability).*
>
> *Weakening of Natural Ocean-Carbon Sinks: The amount of carbon dioxide absorbed by the oceans is likely to weaken in the future through a number of chemical, biological and physical changes. For example, chemical uptake processes may be exhausted, warming surface waters will reduce the rate of absorption and* CO_2 *absorbing organisms are likely to be damaged by ocean acidification. Most carbon cycle models agree that climate change will weaken the ocean sink, but suggest that this would be a smaller effect than the weakening of the land sink."*

Re-absorption occurs within a context of natural carbon cycles which involve very large natural transfers of CO_2 to and from the atmosphere every year, the largest being transfers to/from plant life and to/from the oceans. Moreover these transfer processes are themselves affected both by general and specific aspects of climate, by temperature and by the prevailing atmospheric concentration level of CO_2. In other words the actual re-absorption rate is endogenously determined within the climatic system and can therefore only be stated within a particular context; over time the strength of these processes may alter as changes in climate take place. For example some terrestrial and oceanic

[20] *Stern Review on the Economics of Climate Change*. HM Treasury. October 2006.

carbon sinks may become CO_2 saturated, with a cumulative absorption limit that depends on a variety of climatic and other factors.

These two fundamental features, the endogeneity of carbon re-absorption, and the fact we should be concerned with the incremental effect of extra emissions rather than the fate of a particular molecule of CO_2, have not hitherto been well explained in much of the climate literature. This has led to quotation of some confusing and potentially misleading figures to describe the life of CO_2 in the atmosphere. This is very well expressed in a recent article in Nature[21]:

> *"It doesn't help, though, that past reports from the UN panel of climate experts have made misleading statements about the lifetime of CO_2 ..... The first assessment report, in 1990, said that CO_2's lifetime is 50 to 200 years. The reports in 1995 and 2001 revised this down to 5 to 200 years. Because the oceans suck up huge amounts of the gas each year, the average CO_2 molecule does spend about 5 years in the atmosphere. But the oceans also release much of that CO_2 back to the air, such that man-made emissions keep the atmosphere's CO_2 levels elevated for millennia. ....*
>
> *Earlier reports from the panel did include caveats such as "No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes." The IPCC's latest assessment, however, avoids the problems of earlier reports by including similar caveats while simply refusing to give a numeric estimate of the lifetime for carbon dioxide. Contributing author Richard Betts of the UK Met Office Hadley Centre says the panel made this change in recognition of the fact that "the lifetime estimates cited in previous reports had been potentially misleading, or at least open to misinterpretation."*
>
> *Instead of pinning an absolute value on the atmospheric lifetime of CO_2, the 2007 report describes its gradual dissipation over time, saying, "About 50% of a CO_2 increase will be removed from the atmosphere within 30 years, and a further 30% will be removed within a few centuries. The remaining 20% may stay in the atmosphere for many thousands of years." But if cumulative emissions are high, the portion remaining in the atmosphere could be higher than this, models suggest."*

Other papers have suggested that increasing CO_2 concentration, and its associated climate effects, may have an adverse effect on the carbon cycle and in particular on the ability of certain sinks to absorb more carbon. Stern quotes a recent study[22] to warn that, if feedbacks between the climate and carbon cycle are included in a climate model, the resulting weakening of natural carbon absorption means that allowable cumulative emissions consistent with stabilisation are dramatically reduced.

Actual re-absorption depends on a wide range of factors, and will change over time with the state of other climate and climate system variables. For example one feature of terrestrial and oceanic carbon sinks is that they may become saturated, but their cumulative absorption limit is likely to depend on a variety of climatic and other factors, and will not necessarily be driven directly by CO_2 concentration levels.

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[21] Nature. 20 November 2008. http://www.nature.com/climate/2008/0812/full/climate.2008.122.html

[22] Jones, C.D., P.M. Cox and C. Huntingford (2006): *'Impact of climate-carbon feedbacks on emissions scenarios to achieve stabilisation'*, in Avoiding Dangerous Climate Change, Schellnhuber et al. (eds.), Cambridge: Cambridge University Press.

It is not meaningful therefore to state a simple mathematical relationship between CO_2, re-absorption rates and concentration levels. Overall current scientific understanding on the subject, however, suggests that current re-absorption rates, measured in relation to incremental emissions, are low, of the order of 1% pa, but may turn out to be much lower.

2. *Comparing the damage between earlier and later emissions*

The observation that emission of (cumulative) CO_2 this year should carry a higher SCC, and by implication a higher cost penalty, than the same quantity emitted next year, may be intuitively obvious. The algebra below is intended merely to confirm this intuition.

Let D_n be the economic damage over all future years attributed to an incremental unit that exists in the atmosphere in year n only, discounted back to year 0. Let Z_n be total impact over all years, ie an infinite series, of a one-off **emission** in year n of volume K, discounted back to year 0. [NB In this formulation impacts are always discounted back to the base year.]

Let the reduction factor V, assumed for simplicity to be constant, be the proportion of incremental CO2 ***not*** re-absorbed after a year, so that the proportion remaining after n years is V^n. [note that V =1 if there is no re-absorption.]

Now let us compare Z_0 and Z_1 as the total effects of the same emission K, but a year apart.

$$Z_0 = K \times D_0 + V \times K \times D_1 + V^2 \times K \times D_2 + \dots + V^n \times K \times D_n + \dots$$

$$Z_1 = K \times D_1 + V \times K \times D_2 \dots + V^{n-1} \times K \times D_n + \dots$$

$$\text{So } Z_0 = K \times D_0 + V \times [K \times D_1 + V \times K \times D_2 \dots + V^{n-1} \times K \times D_n + \dots]$$

$$= [K \times D_0] + [V \times Z_1]$$

Hence unless D_0 is zero or negative, the impact of emission in year 0 must be greater than the impact of emission in year 1 times the reduction factor; i.e., if the reduction is 1% pa, then SCC cannot increase by more than 1% pa.

If V=1, and the CO_2 is purely cumulative, then Z_0 is always greater than Z_1.