Centre for Climate Change Economics and Policy

Grantham Research Institute on Climate Change and the Environment

Environmental prices, uncertainty and learning

Simon Dietz and Samuel Fankhauser

November 2009

Centre for Climate Change Economics and Policy Working Paper No. 12

Grantham Research Institute on Climate Change and the Environment

Working Paper No. 10

The Grantham Foundation for the Protection of the Environment

ESRC Economic & Social Research Council

University of Leeds

LSE The London School of Economics and Political Science

The Centre for Climate Change Economics and Policy (CCCEP) was established by the University of Leeds and the London School of Economics and Political Science in 2008 to advance public and private action on climate change through innovative, rigorous research. The Centre is funded by the UK Economic and Social Research Council and has five inter-linked research programmes:

1. Developing climate science and economics
2. Climate change governance for a new global deal
3. Adaptation to climate change and human development
4. Governments, markets and climate change mitigation
5. The Munich Re Programme - Evaluating the economics of climate risks and opportunities in the insurance sector

More information about the Centre for Climate Change Economics and Policy can be found at: http://www.cccep.ac.uk.

The Grantham Research Institute on Climate Change and the Environment was established by the London School of Economics and Political Science in 2008 to bring together international expertise on economics, finance, geography, the environment, international development and political economy to create a world-leading centre for policy-relevant research and training in climate change and the environment. The Institute is funded by the Grantham Foundation for the Protection of the Environment, and has five research programmes:

1. Use of climate science in decision-making
2. Mitigation of climate change (including the roles of carbon markets and low-carbon technologies)
3. Impacts of, and adaptation to, climate change, and its effects on development
4. Governance of climate change
5. Management of forests and ecosystems

More information about the Grantham Research Institute on Climate Change and the Environment can be found at: http://www.lse.ac.uk/grantham.

Environmental prices, uncertainty and learning

Simon Dietz

Grantham Research Institute on Climate Change and the Environment, and Department of Geography and Environment, London School of Economics and Political Science (LSE), Houghton Street, London WC2A 2AE, UK

Contact details: e-mail: s.dietz@lse.ac.uk
tel.: +44 (0) 207 955 7589
fax: +44 (0) 207 106 1241

Samuel Fankhauser

Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science (LSE), Houghton Street, London WC2A 2AE, UK

Contact details: e-mail: s.fankhauser@lse.ac.uk
tel.: +44 (0) 207 106 1220
fax: +44 (0) 207 106 1241

November 2009[1]

[1] This paper has benefitted greatly from discussions with, and comments from, Alex Bowen, Dieter Helm, Cameron Hepburn, Dimitri Zenghelis and one anonymous referee, as well as participants at an editorial seminar for the Oxford Review of Economic Policy on September 9th 2009. Our research has been supported by the Grantham Foundation for the Protection of the Environment, as well as the Centre for Climate Change Economics and Policy, which is funded by the UK's Economic and Social Research Council (ESRC) and by Munich Re. The usual disclaimers apply.

Environmental prices, uncertainty and learning

Abstract

There is an increasing demand for putting a shadow price on the environment to guide public policy and incentivise private behaviour. In practice, setting that price can be extremely difficult as uncertainties abound. There is often uncertainty not just about individual parameters but about the structure of the problem and how to model it. A further complication is the second-best nature of real environmental policy making. In this paper, we propose some practical steps for setting prices in the face of these difficulties, drawing on the example of climate change. We consider how to determine the overall target for environmental protection, how to set shadow prices to deliver that target, and how we can learn from the performance of policies to revise targets and prices. Perhaps most significantly, we suggest that estimates of the marginal cost of environmental protection, rather than the marginal benefit, will often provide the more consistent and robust prices for achieving targets.

Keywords

Climate change; cost-benefit analysis; emissions trading; learning; model uncertainty; shadow price

JEL codes

Q51; Q52; Q54; Q58

1. Introduction

Governments are increasingly making use of pricing as a means to protect the environment. This includes the proliferation of environmental taxes and cap-and-trade schemes, but it more generally includes the use of prices on environmental goods and services in appraisal of public policies and projects. Cost-benefit analysis is now widely practised, including in the area of environmental protection (Pearce, Atkinson et al. 2006). In other policy areas, environmental prices will also usually need to be applied. In a number of countries, including the United Kingdom and the United States, there is now a legislative requirement across the board to conduct a cost-benefit analysis of significant new policies and policy reforms.

This places greater and greater importance on the methods of pricing environmental goods and services. In an introductory textbook, this is apparently straightforward – some careful modelling of the costs and benefits of environmental protection at the margin will reveal the price of the good at the social optimum, a lá Pigou (1920). But in the real world there are many complications, which make the best course of action much less clear.

Chief among these is the significant uncertainty about the benefits and costs of environmental protection. Moreover, the uncertainty is not just about parameter values – which would allow analysts to work with standard risk tools – but about the structure of the underlying problem and how it should be modelled. Indeed, the analyst will frequently be confronted with a number of competing models. In addition to uncertainty, environmental policy making in the real world presents numerous complexities, which apparently further increases the distance between the problems that the policy maker must resolve and the solutions proposed in the basic textbook analysis.

In this paper, we explore practical ways in which prices may be set in this context. Our motivating example is climate change, where these complications are particularly acute. However we will have cause to mention a number of other environmental problems, such as the pricing of ecosystem services, air pollution control and transportation.

We begin in section two with an outline of the problem of model uncertainty in environmental economics. In section three, we draw some lessons on how to set the target level of environmental protection given model uncertainty, and how to set shadow prices as instruments to achieve the target. We make the obvious point that, if there is uncertainty as to what is the 'best' model of the environmental problem, then policy makers should look to many models for evidence on the benefits and costs of protection in setting targets. Moreover they should look beyond the full set of models, taking a reasoned view on elements of the problem that none of the models adequately represents. We go on to consider how to set the shadow price as an instrument to achieve the target. In this role, we propose two criteria that prices should fulfil – consistency and robustness. In the case of climate change – and we suspect in other cases – these call for prices to be set against estimates of the marginal cost of environmental protection, rather than the marginal benefit.

In sections four and five, we introduce the prospect of learning more about the benefits and costs of protection over time. In principle, a number of insights emerge here. One is the effect of the prospect of learning, allied to the existence of irreversible environmental damage and/or irreversible investments to protect the environment, on the initial target. Another is how uncertainty in integrated environment-economy models can indicate where the value of information is highest and thus where research efforts might usefully be directed. But we focus most of our attention on how policy makers can learn from the revealed cost of existing policies to protect the environment, in order to revise targets and prices. While holding much promise, we navigate various complications attached to the 'second-best' nature of real policies, which make the potential to learn less clear.

Section six concludes. It notes that, in climate change, we have seen a progression in shadow pricing approaches that in many respects mirrors our story. Price setting has evolved from an approach based on modelling the marginal benefits (or symmetrically the social costs) of environmental protection, to an approach based on modelling the marginal costs of protection, and now increasingly into an approach that uses the revealed costs of policy, where they can be demonstrated to be appropriate. The marginal benefit or social cost approach is associated with the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC: Pearce, Cline et al. 1996) and the initial attempt by the UK Government to establish a shadow price of carbon for the appraisal of public investments (Clarkson and Deyes 2002). In subsequent revisions of its guidance on the shadow price of carbon, the UK moved to marginal abatement costs (Price, Thornton et al. 2007). Marginal abatement cost estimates have also recently been used to make recommendations on a carbon tax in France (Rocard 2009). The move to policy-based shadow pricing is exemplified by the UK's Committee on Climate Change (2008), which used estimates of the market price in 2020 for allowances in the European Union Emissions Trading Scheme (EU ETS) to determine the indicative abatement potential in the non-traded sectors of the economy.

2. Model uncertainty in environmental economics

In principle, how to set environmental prices is one of the basic insights of environmental economics, drawing on Pigou's (1920) classic analysis – calculate a marginal benefit function for provision of an environmental good or service, a marginal cost function, and find the price (and by duality) quantity that maximises net benefits. Of course, in practice there are many complications, but perhaps the most severe is uncertainty about both benefits and costs.

This uncertainty is pervasive, not being confined to more celebrated cases such as anthropogenic climate change (Pindyck 2007). Moreover – and this is the crucial point for our paper – it is not of a kind reducible merely to uncertainty about a set of key parameters. Rather, there is usually a deeper uncertainty about what is the best model to build to represent an environmental problem, which is to say that in addition to, or indeed underlying, parameter uncertainty there is model uncertainty.[2] This is crucial, because model uncertainty greatly reduces our confidence in using standard risk tools, such as solving the benefit-cost problem in expectations or calculating the option price of environmental protection, as we are unable to agree on the 'best' model of the system and its probabilities. This is often regarded in the sciences as a situation of 'deep uncertainty' (see e.g. Lempert, Groves et al. 2006), while economists have tended to distinguish it as a situation of uncertainty (Keynes 1921; Knight 1921) or ambiguity (Ellsberg 1961), as opposed to risk.

Model uncertainty has become a relatively familiar problem in, for example, macroeconomics, where the failures of models to provide accurate forecasts of many recent trends are well known.[3] In any given macroeconomic model, there will be parameter uncertainty, for example about the various elasticities of supply and demand. But at least as important is model uncertainty, one manifestation of which is the well-worn debate between advocates of various types of computable

[2] Here as in many cases there are variations in terminology between economics and the sciences. Stainforth *et al*. (2007), for example, define what economists would understand to be parameter uncertainty as model uncertainty, and model uncertainty in turn as 'model inadequacy'.
[3] Most recently the global economic downturn of 2008/9.

general equilibrium (CGE) model, in which the dynamics of the economy are rooted in axioms of microeconomic behaviour, and advocates of models in the Keynesian tradition.[4] One of the principal reasons for this debate is that the economic system is complex and in places poorly understood, such that there is a fundamental debate about the best structure of model to build to represent it. These difficulties are only intensified for environmental problems such as climate change, where reductions in greenhouse gas emissions depend on the large-scale introduction of new technologies into the economy (see Koehler, Grubb et al. 2006).

Model uncertainty is also a familiar problem in the environmental sciences, despite the fact that environmental models often represent physical, chemical and biological processes, which are fairly precisely understood under controlled (e.g. laboratory) conditions. The problem is that the environmental systems under investigation are usually open systems and are typically highly space- and time-specific. In order to maintain analytical tractability, however, the modeller is invariably forced to introduce artificial boundaries and to aggregate, both of which processes encode important and uncertain assumptions (Beven 2008).

Environmental economics has of course to contend with model uncertainty in representing both the economy and the environment. Moreover, perhaps the greatest source of model uncertainty is the crucial linkage between the two, specifically how the environment provides economic value, where the modelling tradition is recent and small in comparison with modelling the economy or the environment alone. For example, Watkiss and Downing (2008) made an inventory of possible impacts of climate change on human wellbeing and analysed the coverage of these impacts by the current crop of integrated assessment models (IAMs). They found that a significant subset of these impacts, typically the most uncertain but at the same time most damaging, were not explicitly modelled by any of the IAMs.[5] Another such example is the conservation of ecosystems and biodiversity, where their contribution to human wellbeing is one of the most poorly understood elements of the policy problem (Millenium Ecosystem Assessment 2005).

3. Setting targets, and prices to deliver targets

[4] Pagan (2003) provided an interesting review of these issues in a report on modelling and forecasting practices in the Bank of England.

[5] Weitzman (2009) considers this mismatch in thinking about the functional form of the damage or loss function connecting rises in global temperature with changes in human wellbeing.

How then should policy makers set environmental prices given model uncertainty? One very important consideration is the capacity to learn more about benefits and costs, so that uncertainty is reduced over time. But we discuss learning in the following section, choosing here to begin our discussion with a simpler, static question – what price should we set in the first place?

To begin with, it is useful to distinguish between targets for environmental protection, and instruments to deliver them.[6] In this paper we are primarily concerned with prices as an instrument to deliver targets, whether that be through the use of explicit price instruments such as taxes and subsidies, quantity instruments such as cap-and-trade schemes that set an implicit price, or through pricing the environment in policy and project appraisal. Conceptually, of course, setting the target for protection is itself a form of price determination, so prices are relevant both to target and instrument choice, and our discussion of model uncertainty above has implications in each case.

In the context of target setting, one conclusion, which we presume is of near universal import and which follows from the preceding discussion, is that policy makers should look to many models for evidence on the benefits and costs of environmental protection. Indeed, they should also look beyond the full set of models, taking, with due care paid to familiar weaknesses in human judgement under uncertainty (Kahneman, Slovic et al. 1982), a reasoned view on elements of the problem that none of the models represents adequately. The Bank of England's Monetary Policy Committee provides a useful analogy here – its decisions on interest rates are supported by the Bank's suite of models[7], and the Committee exercises its own collective judgement on, and in addition to, this evidence.

A related point is the familiar disclaimer of cost-benefit analysis, namely that CBA is merely one of many inputs to policy making. The reasons for applying this disclaimer extend beyond model uncertainty. Usually what analysts have in mind is the set of normative and political considerations that is not generally incorporated in CBA (which is not to say that CBA is devoid of value judgements, a point to which we shall return below). The IPCC's regular series of Assessment Reports on climate change is one example of the qualified use of economic analysis.

[6] See Hepburn (2006) for a stylised discussion of the regulatory process and the choice between price and quantity instruments.
[7] Although Pagan (2003) has criticised the suite of models for having been put together more out of convenience than any explicit aim to compile a suitable set of models.

The Third Assessment Report (IPCC 2001) summarised the benefits of carbon abatement in five 'reasons for concern', which provide what is in our view a fairly good example of how various decision-relevant measures of environmental damage, economic and non-economic, can be transparently but succinctly combined. The reasons for concern were: (i) risks to unique and threatened systems; (ii) risks from extreme climate events; (iii) distribution of impacts; (iv) aggregate impacts (i.e. quantifiable economic benefits on aggregate[8]); and (v) risks from future large-scale discontinuities (essentially climate 'catastrophes'). They have recently been updated in Smith *et al*. (2009). Ultimately though, in setting the overall target, there is no substitute for comparing the economic benefits and costs of providing an environmental good or service.

In the context of prices as instruments to deliver targets, we draw further conclusions. We suggest that prices should fulfil two criteria – (a) consistency and (b) robustness. That is to say, they should give us confidence that the targets set can be delivered. To satisfy criteria (a) and (b), we further argue that prices should initially be set against model-based estimates of marginal cost, rather than marginal benefit. To explain why, our motivating example is climate change, but because many other environmental problems would seem to share the same comparative structure of uncertainty about benefits and costs, we expect the analysis to apply more widely.

Figure one is a stylistic representation of uncertainty about the benefits and costs of reducing greenhouse gas (specifically CO_2) emissions, with parameter and model uncertainty conflated. The functions of the marginal external cost of CO_2, which has come to be known as the social cost of carbon (SCC), and the marginal abatement cost of CO_2 (MAC) are depicted as wide bands. Under such uncertainty, the possible set of socially optimal emissions targets runs from E′ to E′′. At any given quantity of emissions in this interval, the MAC could be greater than the SCC, equal to it, or less than it.

FIGURE ONE HERE

Figure one shows that in the case of climate change, uncertainty about the marginal benefits of protection (i.e. here, the SCC) is greater than uncertainty about the marginal costs (MAC). In Tol's

[8] Although it is confined to impacts of climate change on production of marketable commodities (i.e. 'direct use' values in the terminology of environmental valuation).

(2007) meta-analysis, the full range of estimates from 47 published studies of the present[9] SCC runs from –US$1.8 per tonne of CO_2 to ~ $654/t$CO_2$. It is not clear from the meta-analysis how these estimates depend on the quantity of emissions, but research has tended to show that it is not a major source of uncertainty (figure one depicts this, compared with greater sensitivity of the MAC to emissions), so we can take Tol's range to be indicative of the uncertainty at any given quantity of emissions (Pearce 2003; Hope 2005). The mean of the sample is ~ $35/t$CO_2$, illustrating that the distribution of estimates has a large skew or, loosely speaking, a fat tail (see also Weitzman 2009). In turn, since in climate change we are thought to face a large, systematic risk to the economy and human wellbeing, the range incorporates a significant cost of risk bearing, illustrating how value judgements about aversion to risk are present in economic analyses like this.

While it is hard to find a meta-analysis of the MAC working in precisely the same numéraire, Fisher *et al*. (2007), contributing to the Fourth Assessment Report of the IPCC, plot carbon prices in 2030, which various models estimate are necessary to deliver particular emissions targets. Uncertainty in the MAC has been shown to increase strongly as the emissions target tightens, so to place an upper bound on the range we take an ambitious abatement path, stabilising the atmospheric stock of greenhouse gases at around 500 parts per million CO_2-equivalent (putting us on the left-hand side of figure one). In other words, because the comparison of SCC and MAC uncertainty depends on the assumed quantity of emissions, we choose the quantity of emissions with the highest range of the MAC, in order to make the most exacting comparison we can.

In this scenario, Fisher et al. (2007) estimate that the MAC ranges from ~ $0/t$CO_2$ in 2030 to ~ $150/t$CO_2$.[10] Since most models of emissions abatement assume that the carbon price rises at the rate of interest according to the Hotelling principle, we can make a first pass at estimating what the present MAC would be by simply discounting back to today using an interest rate consistent with such modelling studies. Taking this interest rate to be 4%, the range of the present MAC is ~ $0 to ~ $68/t$CO_2$, which is a factor of ten narrower than the uncertainty around the SCC.[11]

---

[9] These studies date from 1982 onwards, and different models have different base years, so in practice what is meant by the 'present SCC' can vary by two decades or so.

[10] Kuik, Brander et al. (2009) perform a similar meta-analysis, and estimate approximately the same range for the MAC, albeit with a higher minimum and maximum.

[11] And it is itself likely to be an overestimate of the range of the present MAC, since the difference in the carbon price between modelling studies tends to increase over time due to the rising importance of differences in assumptions about technological change.

What this rough comparison of uncertainty reveals is an underlying situation in which models of the SCC are more uncertain than models of the MAC. The fundamental reason for this is that the former rely on an evidence base that is much more meagre than the latter (Dietz and Stern 2008). As we mentioned above, there is a lack of evidence concerning the economic value of environmental changes as a result of changes in the climate (Watkiss and Downing 2008). In addition, due in large part to possible non-linearities in the system, we are highly uncertain about what climatic changes to expect (Stainforth, Allen et al. 2007). Indeed, such non-linearities are present in many environmental systems and explain why few of them are well understood (Pindyck 2007). Even local environmental pollution offers up examples – freshwater lakes often exhibit the potential to abruptly switch to a euthrophic state at some unknown concentration of nutrient pollution (Scheffer, Carpenter et al. 2001). This can be contrasted with MAC models. Here, uncertainties are also present, but there is generally more evidence available to constrain the structure and parameterisation of the model. For example, the cost of new emissions abatement technologies is one of the key uncertainties in most MAC models, but, even here, the technologies that are assumed to be deployed in meeting emissions targets are already commercially available at known prices (i.e. MAC models generally work with proven technologies).

In cases such as this where the model uncertainty around marginal benefits is much greater than around costs, we suggest that a robust strategy is to make greater use of marginal costs in setting prices, rather than marginal benefits. However, care must be taken to avoid an obvious circularity. While marginal costs can often give us greater assurance that a given target can be met, clearly they cannot be used alone to set that target, since we have no information about the benefits of emissions reductions. This is where marginal benefits still have a role to play, alongside a broader set of evidence.

In addition, use of marginal costs can provide greater consistency with overall targets. The reason is that models of abatement/protection are more often than not explicitly run to deliver pre-determined quantities of environmental goods (i.e. cost-effectiveness analysis), so consistency is assured by definition. Parameters that are controversial in the context of cost-benefit analysis, notably the discount rate, are set based on what private agents would actually be likely to face in the market. By contrast, it is often difficult to identify whether estimates of the marginal benefit of protection have been made in a model with assumptions consistent with the chosen target. Again using climate change as an example, it may be that an emissions trajectory was chosen as the basis for the modelling, which is different to that implied by the target. It may be also be that a discount rate was chosen, which could not support the target that was chosen (being e.g. too high). Thus the world's largest emitters have made broad commitments to emissions reductions that would be difficult to justify using the standard discount rate employed in Nordhaus' well-known IAM studies (e.g. Nordhaus 2008).

4. Learning about targets and prices

How does the prospect of learning more about the benefits and costs of environmental protection affect our discussion? First, economic theory shows that the optimal target under uncertainty can change *at the outset* if one expects uncertainty to be reduced in the future, especially if the costs of protection and/or the costs of environmental damage are irreversible.[12] Irreversibilities will be a feature of many environmental problems. Frequently, environmental damage will itself be effectively irreversible, as with the loss of natural ecosystems to development and with the accumulation of CO_2 in the atmosphere.[13] Equally, there are quite likely to be sunk costs to protecting the environment, such as investing in capital equipment to reduce pollutant emissions. What the theory tells us is that the adjustment to the optimal target to reflect learning is ambiguous – it could increase environmental protection, or decrease it, depending on a complicated set of factors, including not only the existence of binding irreversibility constraints in the environment and in investments to protect it, but also, in a by now familiar refrain, on the assumed model of the policy maker's preferences, such as over risk (e.g. the particular utility function that is assumed to be appropriate, and its parameterisation). Unfortunately for a problem whose solution is ambiguous in theory, relatively little empirical work has been done that could support such adjustments (Pindyck 2007)[14], certainly in comparison with the relative outpouring of estimates of the costs and benefits of protection in the absence of learning/irreversibility. At present, then, these considerations can only inform policy in a qualitative way.

---

[12] Important contributions to this literature include Arrow and Fisher (1974), Henry (1974) and Gollier et al. (2000), while Ingham and Ulph (2005) provide a recent review applied to climate change.

[13] If a technology were deployed to remove CO_2 from the atmosphere, accumulation of atmospheric CO_2 would no longer be irreversible, but there would still be a cost to removing it, which would bear upon the initial decision of how much to emit.

[14] Examples include Kolstad (1996), Nordhaus and Popp (1997), and Ulph and Ulph (1997), all of whom consider learning and irreversibility in the context of climate change.

Second, models of uncertain benefits and costs can be used to estimate the value of obtaining more information about elements of the policy problem, and thus to guide decisions on how to allocate resources for further research. This is one area where integrated environment-economy models such as the IAMs applied to climate change can be particularly useful, as they can produce insights that would not otherwise have been obvious. For example, climate-change IAMs have tended to show that uncertainty about optimal emissions reductions is as much due to the economic aspects of the model as it is to the physical aspects (Nordhaus and Popp 1997; Hope 2006), and that some of the principal economic 'uncertainties' have a normative flavour (e.g. the discount rate). As we have warned, the predictive power of IAMs must be assumed to be low, so that considerable caution should be exercised in drawing quantitative conclusions about the value of information, but they have helped us to understand qualitatively where information may be of most value.

Third, information about the benefits and costs of protection should allow us over time to revise targets and prices, and improve models. In particular, we are likely to be able to learn relatively quickly about many of the uncertainties characterising the cost of environmental protection, by looking at the revealed cost of policies that have been introduced (or in the case of a price instrument, the revealed quantity of protection obtained at the price initially set). Here we can draw a further analogy with the Bank of England's Monetary Policy Committee, which, for all its modelling support, receives rapid information about the real economic response to changes in policy such as interest rates, and can adjust them accordingly. However, once again, there are various complications associated with the reality of environmental policy design and implementation that need to be considered, and we do so in the next section.

5. Learning from the revealed cost of existing policies

To begin with, most environmental targets are accompanied by a range of policy instruments, sometimes overlapping, and the revealed compliance costs of these policies will vary widely. For example, Pearce (2003) compared the revealed cost of a selection of the UK's most important policies related to abating carbon emissions (our choice of words is deliberately careful here). These included the Climate Change Levy, which is a tax on the consumption of fossil fuels and electricity by industry, the Fuel Duty Escalator, which is a formula to regularly increase the tax rate on petroleum road fuels[15], and the Renewables Obligation, a requirement on electricity suppliers to source a certain share of their total supply from renewable technologies. He found that the revealed cost of carbon abatement varied markedly across (and even within) these policies. The revealed cost of carbon in the Climate Change Levy varied from ~ £4.36/tCO_2 for coal to ~ £8.45/tCO_2 for electricity, because the tax rate did not correspond directly to the carbon content of the energy. The revealed cost of the Fuel Duty Escalator, estimated as the real increase over the period 1993-1999, was ~ £73.69/tCO_2 for gasoline and ~ £80.11/tCO_2 for diesel. The revealed cost of the Renewables Obligation was ~ £84.47 tCO_2.

There are good reasons and bad reasons for why policy costs may differ, so it is important to understand the basis of discrepancies. If the reasons are sound, all that needs to be done is to account for differences in context when estimating revealed costs, even though this is less than straightforward in practice (see below). If the reasons are bad, one would ideally go further and consider changing policy.

A common reason why environmental costs differ across context is that the policies in question exist to meet several objectives. Take for instance duty on road fuels. Consumption of road fuels leads not only to carbon emissions, but also to other forms of pollution such as local air pollution and noise. In addition, motoring leads to congestion costs and to road accidents (see e.g. Maddison, Pearce et al. 1996). In a country such as the UK fuel duty is also a major source of government revenue.

Therefore an analysis such as Pearce's (2003) faces a form of inverse-optimum problem – estimating the portion of the revealed policy cost attributable to the carbon externality. In his case, the assumption was that all of the policy cost was incurred to correct the climate-change externality. The basis for such an assumption may be political statements, but it may be unwise to take them at face value. Revealingly, Pearce (2003) noted that different justifications had been offered for the Fuel Duty Escalator at different times. Alternatively, one can attempt to estimate the optimal tax on a commodity such as road fuel from first principles (i.e. pricing each argument in the optimal tax separately - e.g. Parry and Small 2005), but, as far as environmental externalities

[15] The Fuel Duty Escalator was introduced by the British Government in 1993 with the expressed purpose of reducing carbon emissions, temporarily withdrawn due to protests in 2000, before being reinstated in 2008.

are concerned, this typically relies on estimates of marginal benefits, something we have cautioned against on the grounds of uncertainty.

Whether the attempt to meet several policy objectives with the same policy should be considered 'good' or 'bad' is a classic application of the theory of second-best. In a first-best world, each policy objective related to consumption of road fuel would be corrected using the most efficient instrument. In general this requires at least as many instruments as there are objectives, as Tinbergen famously established (1952). While air pollution and greenhouse gas emissions are indeed perhaps best covered through a tax on fuel consumption, the best policy lever for congestion, which is highly place- and time-specific, would likely be direct congestion pricing. In the case of accidents it would likely be a distance-based charge, since accident risk is proportional to distance travelled, *ceteris paribus* (Parry, Walls et al. 2007). If for some reason these policy instruments are unavailable, then the second-best alternative may well be to price them into fuel duty. In addition, fuel tax could be an efficient means to raise government revenue compared with labour taxation (Parry and Small 2005; West and Williams III 2007).

Another reason why revealed policy costs differ is concern about the distributional impact of a particular policy. How distributional concerns should best be tackled across the basket of instruments at the policy maker's disposal has been a matter of contention in economics for many years. Tools with which distributional concerns can be taken into account when setting prices (such as equity weights) have been developed (Squire and van der Tak 1975; Fankhauser, Tol et al. 1997), although they are not widely used. Typically distributional issues are dealt with 'outside the model'. More problematic still are policy capture and vested interests, that is, deviations that reflect the influence of special interests on government policy. Most economists would see these as bad reasons for differing environmental prices.

Another common problem in learning from existing policies is that the policies in question may be inconsistent with the overall environmental target. The United States, for example, has a vibrant voluntary carbon market, centred around the Chicago Climate Exchange. The prices quoted are generally low, in the order of \$2 – 5/tCO_2. They reflect the limited appetite of market participants for onerous unilateral targets more than they reflect the costs of CO_2 to society. As such, the CCX price is clearly unsuitable as an economy-wide shadow price for carbon, although the scheme serves an important environmental purpose in giving participants an incentive to change behaviour. The same probably holds for most payment-for-ecosystem-services schemes, which tend to be voluntary in nature (see e.g. Landell-Mills and Porras 2002; Wunder 2005).

There can also be more subtle shortcomings in policy design. This is particularly the case for complex market instruments like cap-and-trade systems, which require sophisticated regulatory structures. At face value, the price signals from the growing number of environmental markets are ideal indicators of protection costs. The observed price in a well-designed environmental market can be expected to reflect marginal compliance costs much more accurately than any modelling run. However, for markets to reflect opportunity costs accurately they have to work efficiently, and this is a considerable hurdle to pass.

It is well-documented that the structure and design of a market can have a strong impact on the resulting price (Fankhauser and Hepburn 2009). Limits in the ability to bank and borrow allowances between compliance periods, for example, can lead to artificial price fluctuations at the end of a period (Stavins 1998; Pizer 2005). Compliance penalties have a similar effect. They can inflate prices by making non-compliance more costly and incentivising firms to build in safety margins. Alternatively, they may act as a price cap if the penalty is paid in lieu of submitting allowances. Price-stabilising interventions (such as an auction reserve price) have a self-evident effect, although it could be argued that they are there to fine-tune the environmental target in light of new information.

In the early days of an environmental market, before it reaches maturity, prices can also be expected to fluctuate heavily. Reliable information is limited and pricing models are still in their infancy. Trading volumes are still low, insufficient to attract arbitrageurs. Hedging tools like indices and other derivatives are not yet developed. Even when environmental markets mature they may, like all commodities markets, be subject to price fluctuations that owe as much to speculation as to market fundamentals (see Paolella and Taschini, 2008, for CO_2 and Pizer, 2005, for price trends in the US air pollution market).

But over time, mature environmental markets will provide increasingly reliable indicators of environmental costs. One market that has probably reached this point is the US market for sulphur, a well-established and successful market that is driven by the regulatory requirements of the 1990 Clean Air Act (see Bohi and Burtraw 1997; Stavins 1998; Ellerman, Joskow et al. 2000).

Arguably, the quoted market price for sulphur is by now a credible shadow price for this pollutant in the US context.

The EU ETS could be another example of a market that provides an increasingly accurate environmental price signal, in this case the shadow price of carbon in Europe. Many of the early teething problems have been overcome (for an assessment of the early ETS experience, see Convery, Ellerman et al. 2008). The market is liquid, with several million tons of carbon traded every day. The target is fully consistent with the EU's climate change objectives. A wide range of carbon-related financial products is available, and a growing number of increasingly experienced analysts are following market trends.

Yet, one must doubt whether the current EU allowance price – an average of €18 since the beginning of 2008, and less than €13 during the first half of 2009[16] – is high enough to reflect the marginal costs of the EU's emissions reduction objectives for 2020 – a 20% cut in emissions relative to 1990 – or for that matter the social cost of carbon.

The missing ingredient is trust in the market long-term. Traders appear to apply a hefty risk premium to the prospects of carbon trading in the long term. Futures market data for the first seven months of 2009 show an implied cost of carry between Dec09 and Dec12 EU allowances of about 5%.[17] That is, the EU allowance price rises at a steady 5% a year per Hotelling's rule. But the cost of carry jumps to almost 8% between Dec12 allowances and the less-traded Dec14, suggesting much less confidence in the market arrangements for phase III, which is to start in 2013. To take a punt on the 2020 carbon price – which is not traded yet but which analysts expect to be above €30 – investors would require a return of over 10% per annum.

As long as these risk premia prevail, the EU allowance price is not an appropriate shadow price of carbon for use in the non-traded sector. But one can speculate that the day when this will change may not be too far away.

6. Conclusions

[16] Spot prices from www.bluenext.eu. Bluenext is the dominant exchange for spot trading.
[17] See www.ecx.eu. The European Climate Exchange (ECX) is the leading platform for futures trading.

Uncertainty is pervasive in environmental policy. There is not just uncertainty about parameter values, for which there are standard risk tools, but about the structure of the underlying problem and how it should be modelled. Climate change is a particular case in point – which has informed much of the analysis in this paper – but it is not the only one. Such deep uncertainty, or ambiguity, presents problems not just for analysis but also for policy. Whatever the state of knowledge, policies must be set and this means, generally, putting a shadow price on the environment.

In the case of climate change at least, the history of economic analysis appears to be following the progression we have set out in this paper, whereby price setting is evolving from a social cost approach into a marginal abatement cost approach and eventually into a policy or market-based approach.

The social cost approach was afforded prominence by the Second Assessment Report of the IPCC (Pearce, Cline et al. 1996), and the UK Government's first attempt to establish a shadow price of carbon for the appraisal of public investments was also based on the social cost of carbon emissions (Clarkson and Deyes 2002). In subsequent revisions of its guidance on the shadow price of carbon, the UK moved to marginal abatement costs (Price, Thornton et al. 2007). Marginal abatement cost estimates have also recently been used to make recommendations on a carbon tax in France (Rocard 2009). An example of the market-based approach is the inaugural report of the UK CCC (CCC 2008; Fankhauser, Kennedy et al. 2009a; Fankhauser, Kennedy et al. 2009b). One of the issues the CCC looked at was the split of the mitigation effort between 'traded sectors' that are covered by the EU ETS and non-traded sectors, like services, that are not. In estimating the emission reduction potentials in non-traded sectors, the CCC used the expected market price in the EU ETS as the indicative cut-off price for abatement action in other parts of the economy.

As we move through this sequence the robustness of the price signal gradually increases. The range of uncertainty in the social cost literature stretches from -\$1.8/tCO_2 to over \$654/tCO_2. Marginal abatement cost estimates vary between \$0 and \$68/tCO_2**.** Fluctuations in the market price of carbon (or more specifically, the price of Dec09 EU allowances) are narrower still, with a historical low of around \$10 and a historical high of just under \$40/tCO_2**.**

However, for each step in the progression, certain conditions have to be met before it makes sense to move to the next approach. In addition, the process is not linear – information obtained at a later step can and should lead to revisions to earlier steps. The social cost approach is an indispensible part of the process of target setting, and moving from social costs to marginal abatement costs requires at least an indicative knowledge of the ultimate target, as marginal abatement costs have to be measured in the vicinity of this target. In the extreme case, the target has already been set (based on social costs and broader considerations) and the problem has become one of cost-effectiveness.

Moving from modelling estimates of marginal abatement costs to policy-based price setting requires confidence in the policy environment from which values are transferred, both in terms of its consistency with the environmental objective and the effectiveness of the instrument. This is a considerable hurdle to meet. Often policies represent multiple objectives (e.g. London's congestion charge, which increasingly combines traffic control with climate-change objectives), the influence of vested interests (e.g. the abolition of Britain's automatic Fuel Duty Escalator following widespread protests) or flaws in policy design (e.g. the price collapse in phase I of the EU ETS).

In climate change, shadow price analysis has arguably progressed from social costs to marginal abatement costs. There is an emerging consensus (informed in part, presumably, by social costs) around stabilising the atmospheric concentration of greenhouse gases at around 450 parts per million, which allows the shadow price of carbon to be set according to the marginal cost of meeting this target. Before long it should be possible to move to market-based pricing and deduce the shadow price of carbon from the observed price in the increasingly liquid and well-functioning carbon market. This will also help us to revise our models of marginal abatement costs, and lead us to reconsider the emissions target.

References

Arrow, K. J. and A. Fisher (1974). "Environmental preservation, uncertainty and irreversibility." Quarterly Journal of Economics **88**: 312-319.

Beven, K. (2008). Environmental Modelling: an Uncertain Future. Abingdon, Oxon, Routledge.

Bohi, D. R. and D. Burtraw (1997). "SO2 allowance trading: how do expectations and experience measure up?" Electricity Journal **10**(7): 67-75.

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

Committee on Climate Change (CCC) (2008). Building a low-carbon economy: the UK's contribution to tackling climate change. London, The Stationery Office.

Convery, F., D. Ellerman, et al. (2008). The European Carbon Market in Action. Lessons from the First Trading Period. Report No. 162. Massachusetts Institute of Technology, MIT Joint Programme on the Science and Policy of Global Change.

Dietz, S. and N. Stern (2008). "Why economic analysis supports strong action on climate change: a response to the Stern Review's critics." Review of Environmental Economics and Policy **2**(1): 94-113.

Ellerman, D., P. L. Joskow, et al. (2000). Markets for Clean Air, The US Acid Rain Program. Cambridge, Cambridge University Press.

Ellsberg, D. (1961). "Risk, ambiguity and the Savage axiom." Quarterly Journal of Economics **75**(4): 643-669.

Fankhauser, S. and C. Hepburn (2009). Carbon Markets in Time and Space. Background Paper for the Lazerowicz Review. London, Department of Energy and Climate Change.

Fankhauser, S., D. Kennedy, et al. (2009a). "Building a low-carbon economy: the inaugural report of the UK Committee on Climate Change." Environmental Hazards **8**: 1-8.

Fankhauser, S., D. Kennedy, et al. (2009b). The UK's carbon targets for 2020 and the role of the Committee on Climate Change. Building a Low-Carbon Future: the Politics of Climate Change. A. Giddens, S. Latham and R. Liddle. London, Policy Network.

Fankhauser, S., R. S. J. Tol, et al. (1997). "The aggregation of climate change damages: a welfare theoretic approach." Environmental and Resource Economics **10**: 249-266.

Fisher, B. S., N. Nakicenovic, et al. (2007). Issues related to mitigation in the long term context Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change. B. Metz, O. R. Davidson, P. R. Bosch, R. Dave and L. A. Meyer Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press: 169-250.

Gollier, C., B. Jullien, et al. (2000). "Scientific progress and irreversibility: an economic interpretation of the precautionary principle." Journal of Public Economics **75**: 229-253.

Henry, C. (1974). "Investment decisions under uncertainty: the irreversibility effect." American Economic Review **64**: 1006-1012.

Hepburn, C. (2006). "Regulating by prices, quantities, or both: a review of instrument choice." Oxford Review of Economic Policy **22**: 226-247.

Hope, C. (2005). Integrated assessment models. Climate-Change Policy. D. Helm. Oxford, Oxford University Press: 77-98.

Hope, C. (2006). "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.

Ingham, A. and A. Ulph (2005). Uncertainty and climate-change policy. Climate-Change Policy. D. Helm. Oxford, Oxford University Press: 43-72.

IPCC (2001). Summary for Policymakers. Climate Change 2001: Impacts, Adaptation and Vulnerability. A Report of Working Group II of the Intergovernmental Panel on Climate Change. Cambridge, Cambridge University Press.

Kahneman, D., P. Slovic, et al. (1982). Judgement Under Uncertainty: Heuristics and Biases. Cambridge, Cambridge University Press.

Keynes, J. M. (1921). A Treatise on Probability. London, Macmillan.

Knight, F. H. (1921). Risk, Uncertainty and Profit. Boston, Houghton Mifflin.

Koehler, J., M. Grubb, et al. (2006). "The transition to endogenous technical change in climate-economy models: a technical overview to the Innovation Modeling Comparison Project." Energy Journal (Special Issue, Endogenous Technological Change and the Economics of Atmosperic Stabilization): 17-55.

Kolstad, C. (1996). "Learning and stock externalities in environmental regulations: the case of greenhouse gas emissions." Journal of Environmental Economics and Management **31**: 1-18.

Kuik, O., L. Brander, et al. (2009). "Marginal abatement costs of carbon-dioxide emissions: a meta-analysis." Energy Policy **37**(4): 1395-1403.

Landell-Mills, N. and T. I. Porras (2002). Silver Bullet or Fools' Gold? A Global Review of Markets for Forest Environmental Services and their Impact on the Poor. London, International Institute for Environment and Development (IIED).

Lempert, R. J., D. G. Groves, et al. (2006). "A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios " Management Science **52**(4): 514-528.

Maddison, D. J., D. W. Pearce, et al. (1996). Blueprint 5: the True Costs of Road Transport. London, Earthscan.

Millenium Ecosystem Assessment (2005). Ecosystems and Human Wellbeing: Synthesis. Washington, DC, Island Press.

Nordhaus, W. D. (2008). A Question of Balance: Weighing the Options on Global Warming Policies. New Haven and London, Yale University Press.

Nordhaus, W. D. and D. Popp (1997). "What is the value of scientific knowledge? An application to global warming using the PRICE model." The Energy Journal **18**: 1-47.

Pagan, A. (2003). Report on Modelling and Forecasting at the Bank of England. Quarterly Bulletin. London, Bank of England.

Paolella, M. and L. Taschini (2008). "An econometric analysis of emission allowance prices." Journal of Banking and Finance **32**(10): 2022-2032.

Parry, I. W. H. and K. A. Small (2005). "Does Britain or the United States have the right gasoline tax?" American Economic Review **95**(4): 1276-1289.

Parry, I. W. H., M. Walls, et al. (2007). "Automobile externalities and policies." Journal of Economic Literature **45**(2): 373-399.

Pearce, D., G. Atkinson, et al. (2006). Cost-Benefit Analysis and the Environment. Paris, OECD.

Pearce, D. W. (2003). "The social cost of carbon." Oxford Review of Economic Policy **19**(3): 362-384.

Pearce, D. W., W. R. Cline, et al. (1996). The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control. Climate Change 1995: Economic and Social Dimensions - Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. J. P. Bruce, H. Lee and E. F. Haites. Cambridge, Cambridge University Press.

Pigou, A. C. (1920). The Economics of Welfare. London, MacMillan.

Pindyck, R. (2007). "Uncertainty in environmental economics." Review of Environmental Economics and Policy **1**(1): 45-65.

Pizer, W. A. (2005). Climate Policy Design Under Uncertainty. Discussion Paper 05-44. Washington, D.C., Resources for the Future.

Price, R., S. Thornton, et al. (2007). 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. London, Department for the Environment, Food and Rural Affairs.

Rocard, M. (2009). Rapport de la Conférence des Experts et de la Table Ronde sur la Contribution Climat et Énergie. Paris, Ministere de l'Ecologie, de l'Energie, du Developpement Durable et de la Mer, de l'Economie, de l'Industrie et de l'Emploi.

Scheffer, M., S. Carpenter, et al. (2001). "Catastrophic shifts in ecosystems." Nature **413**: 591-596.

Smith, J. B., S. H. Schneider, et al. (2009). "Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern"." Proceedings of the National Academy of Sciences **106**(11): 4133-4137.

Squire, L. and H. C. van der Tak (1975). Economic Analysis of Projects. Baltimore, Johns Hopkins Press.

Stainforth, D. A., M. R. Allen, et al. (2007). "Confidence, uncertainty and decision-support relevance in climate predictions." Philosophical Transactions of the Royal Society A **365**(1857): 2145-2161.

Stavins, R. N. (1998). "What have we learned from the grand policy experiment? Positive and normative lessons from SO2 allowance trading." Journal of Economic Perspectives **12**(3): 69-88.

Tinbergen, J. (1952). On the Theory of Economic Policy. Amsterdam, North Holland.

Tol, R. S. J. (2007). The social cost of carbon: trends, outliers and catastrophes. E-conomics Discussion Papers 2007-44.

Ulph, A. and D. Ulph (1997). "Global warming, irreversibility and learning." Economic Journal **107**: 636-650.

Watkiss, P. and T. E. Downing (2008). "The social cost of carbon: valuation estimates and their use in UK policy." Integrated Assessment **8**(1): 85-105.

Weitzman, M. L. (2009). "On modeling and interpreting the economics of catastrophic climate change." Review of Economics and Statistics **91**(1): 1-19.

Weitzman, M. L. (2009). What is the "damages function" for global warming and what difference might it make?, Harvard University.

West, S. E. and R. C. Williams III (2007). "Optimal taxation and cross-price effects on labor supply: estimates of the optimal gas tax." Journal of Public Economics **91**(3-4): 593-617.

Wunder, S. (2005). Payments for Environmental Services: Some Nuts and Bolts. CIFOR Occasional Paper No 42. Jakarta, Center for International Forestry Research.

Figure 1. The SCC and the MAC under uncertainty.