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Abstract

Estimates of the costs of implementing the Kyoto protocol are uncertain and most are based on assumptions that necessarily imply high costs. A selection of alternative (often more realistic) assumptions gives estimates that suggest net benefits rather than costs. One high-cost estimate is from the US Energy Information Administration but it is based on a rapid short-term adjustment to Kyoto-type targets and the model does not include the flexibility mechanisms. Another high-cost (but long-term) estimate is from the Oxford model and suggests a 4% cost of US GDP by 2020 to achieve Kyoto targets without the flexible mechanisms. It is shown that this estimate is based on a wrong interpretation of the literature, a confusion of short-term with long-run costs, and a selection of worst-case assumptions and parameters. Provided policies are expected, gradual and well-designed, the costs for the US of Kyoto are likely to be insignificant.

Introduction

The high costs for the US economy of mitigating climate change have been cited by the Bush administration as one of the reasons for rejecting US ratification of the Kyoto Protocol. However the estimates of high costs are uncertain and most are based on assumptions that necessarily imply high costs. This paper explores how the modelling approaches and assumptions can give high-cost estimates. In particular it assesses the reasons for the very high estimates from the Oxford model.

The high-cost estimates of greenhouse gas mitigation for the US

The World Resources Institute study

The literature up to 1997 on costs to the US economy in terms of losses in GDP when the Kyoto Protocol was negotiated has been summarised in a comparative study by World Resources Institute (WRI) (Repetto and Austin, 1997). They used econometric regression techniques to assess the role of assumptions in 162 results from 16 models used to project GDP costs of CO_2 mitigation. Most of the studies used a carbon tax explicitly or as an implicit addition to the price of carbon needed to restrict its use. The regression equation explains the percentage change in US GDP in terms of the CO_2 reduction target, the number of years to meet the target, the assumed use of carbon tax revenues (how the revenues are 'recycled' through the economy) and seven model attributes. It estimates that, as a summary of the results of these models, in the worst case combining these assumptions and attributes, a 30% reduction in US baseline emissions by 2020 would cost about 3% of GDP. The corresponding best case implies an increase of about 2.5% in GDP above the baseline. The total difference of 5.5 percentage points (pp) (i.e. 3pp plus 2.5pp) of GDP in lower costs can be attributed to the recycling assumption (1.2pp) and across the attributes (4.3pp as follows):

- general equilibrium models gave lower costs than macroeconometric models (1.7pp)
- the inclusion of averted non-climate change damages, e.g. air pollution effects (1.1pp)

- the inclusion of Joint Implementation and/or international emission permit trading (0.7pp)
- the availability of a constant cost backstop technology (0.5pp)
- the inclusion of averted climate change damages in the model (0.2pp)
- the degree of product substitution in the model (the more the better) (0.1pp)
- the degree of inter-fuel substitution in the model (0.0pp).

Over 70% of the variations in the GDP impacts in the models are explained by these factors and by the size of the CO_2 target reductions.

In summary, the worst-case results suggest that a 30% reduction in CO_2 by 2020 implies a cost of 3% of GDP; these costs come from using a macroeconometric model with lump-sum recycling of revenues, no emission permit trading, no environmental benefits in the model and no non-carbon backstop technology.

The Energy Information Administration (EIA) 1998 study

The EIA in 1998, at the request of the US House of Representatives' Committee on Science, analysed the impacts of the Kyoto Protocol on U.S. energy use, prices, and the general economy by 2008-2012, with actions to achieve the target beginning in 2005. The EIA used Data Resources Incorporated (DRI)'s annual macroeconometric model to assess the general economic effects and concluded that a 7% cut in CO_2 emissions below 1990 levels by 2010 would imply a reduction of 4.2% in GDP below projected levels for 2010. Note that this is *not* the proposed legal commitment of the Kyoto Protocol, which allows for multiple gases and flexible mechanisms, including international permit trading. A reduction in carbon used was assumed to be achieved by a domestic auctioned permit scheme, with revenues from the auctions recycled as lump-sum rebates to income-tax payers.

The high-cost result was acknowledged in the EIA report to be an effect of both high short-term adjustment costs and how the auction revenues are spent. To meet the target, a reduction in total US CO_2 emissions of over 30% is required over the 3-year period 2005-2008 because of two factors:

(1) the high baseline growth of CO_2 emissions from 1990 to 2005; and
(2) the (assumed) delay in taking action until 2005.

The 30% cut requires a massive adjustment in energy structures over a short period. This is largely an avoidable short-term adjustment cost. Using the same model, the EIA reported that if the economy is allowed much longer to adjust, the costs fall from 4.2% of GDP in 2010 to 0.8% in 2020 with lump-sum recycling. The costs fall from 1.9% of GDP in 2010 to a negligible 0.2% in 2020 (US EIA, 1998, Table ES6) assuming that the revenues are used to reduce social security payments by employees and businesses.

Furthermore, even if the 2010 horizon is maintained, the scale of the adjustment costs depends critically on the form in which the revenues are recycled. The costs are reduced from 4.2% to 1.9% of GDP if revenues are recycled through reductions in social security tax rebates. It is also clear from the detailed macroeconomic results that the increase in costs is associated with a large increase in overall consumer prices, as a result of the increases in costs of energy. This suggests that an alternative way of recycling revenues may be even less costly. For example, the revenues could be used to reduce sales taxes, thereby reducing consumer prices and offsetting the energy-price increases.

The Energy Modelling Forum 16 studies on the costs of Kyoto

A series of studies undertaken in a consistent framework of assumptions is reported in a Special Issue of *The Energy Journal* in 1999, following an Energy Modelling Forum (EMF) exercise assessing the costs of adopting elements of the Kyoto Protocol. This report and the exercise are both substantial and influential; the report dominates the literature on the global costs of adopting the Kyoto Protocol.

Weyant and Hill (1999) summarise the studies and the results. All the studies use carbon emission permits as the instrument for mitigation and therefore yield implicit carbon tax rates to achieve the targets; all assume lump-sum recycling of revenues; and all set aside the environmental benefits. Both sets of assumptions have been shown to lead to higher costs (Repetto and Austin, 1997). A consistent range of scenarios is considered by 13 modelling teams, with the emphasis given to how emission-permit trading may reduce costs. Table 1 gives the extreme ends of the range of results for the carbon tax rates and the associated GDP changes coming from the EMF-16 studies.

The most striking feature of the extremes presented in Table 1 is the wide range of the rates of carbon taxes estimated as needed to reach the Kyoto targets by domestic policies using an efficient economic instrument. Although several of the assumptions are consistent across the studies, there is an extra feature (excluded from the WRI study) that gives rise to differences. The Kyoto target is an absolute one in relation to a 1990 or 1995 base, whereas the WRI study considers CO_2 emissions relative to a base line over the projection period. This means that the range in the results in the EMF study is partly due to the different regional targets and different rates of growth of CO_2 emissions in the base projection.

The effectiveness of the carbon tax in achieving a given target in different countries depends on the tax and energy systems in place. If energy is already taxed, then a carbon tax will have to be that much higher in order to push up prices by a given proportion. If the existing energy system is such that there are substantial opportunities to switch from carbon-based energy then the tax will be lower, e.g. if there are substitution possibilities for a switch from relatively high to relatively low carbon fuels, such as from coal to gas. Carbon taxes tend to be estimated at higher levels for Japan and Europe than for the USA, because of the latter’s relatively low energy tax rates.

Table 1: Energy Modelling Forum results for the carbon tax and GDP effects in 2010

	Top of range for tax rate in 2010			Bottom of range for tax rate in 2010		
	Carbon tax US$$_{90}$ per tC	GDP change %	Model	Carbon tax US$$_{90}$ Per tC	GDP change %	Model
USA	410	-1.78	Oxford	76	-0.42	G-Cubed
OECD-Europe[1]	966	-2.08	Oxford	159[3]	-0.55	RICE
Japan	1074	-1.88	Oxford	97	-0.57	G-Cubed
Canada, Australia, New Zealand[2]	425	-1.96	ABARE -GTEM	145[3]	-0.96	RICE

Source: Weyant and Hill (1999, pp. xxxi-xxxiv)

Notes to the Table:

[1] Figure 8b in Weyant and Hill (1999, p. xxxii) refers to The European Union, although the EMF-16 region is OECD-Europe. The latter region is assumed to be the one referred to in the table.

[2] The Oxford study does not report results for this group so the highest tax from the other studies is included in the table. However it does report a carbon tax of $1261(90) per tC for Canada alone (Cooper *et al*, 1999, p.349).

[3] The WorldScan model reported a lower carbon tax of $20(90) per tC for OECD-Europe and $46(90) per tC for CANZ, but these were not included in the table because no GDP losses are reported.

The range of GDP costs shown in Table 1 for 2010 is much narrower than that of the carbon tax rates. A high carbon tax does not necessarily imply high GDP costs. The costs in Japan are lower than in some other regions but there is no strong pattern. However all the GDP effects are negative. It is very likely that this result comes from the assumption in these studies that all the revenues from the carbon tax are returned to the economy by means of lump-sum payments to consumers. This form of recycling implies that the average consumer has a loss in real income from the carbon tax compensated by a gain in wealth from the lump-sum repayment, year by year. In many models the loss and the gain, even if they are the same monetary values, have a net effect of reducing expenditure because spending is modelled as being more responsive to a fall in income than to an equivalent rise in wealth.

In the context of general equilibrium modelling, lump-sum recycling is a neutral means of recycling tax revenues because in theory and by assumption it has no behavioural implications in the model, although it can have substantial effects on the distribution of income. The assumption does provide a benchmark to compare effects for different countries and other forms of recycling. However when the assumption is combined with the usual treatment of the production structure in the EMF-16 modelling, it has the *inevitable outcome* that any carbon tax will entail GDP costs.

These costs are therefore to be expected in the empirical studies with general equilibrium models. What is remarkable in *The Costs of the Kyoto Protocol* (Weyant and Hill, 1999) is that the cost estimates are compared without also mentioning that:

(1) *no* country that has implemented a carbon tax has in fact used this method of recycling the revenues, and
(2) this method of recycling, while convenient for modelling purposes, is economically inefficient and leads to relatively high net costs of abatement[1].

Jorgenson and Wilcoxen argue: "(Lump-sum recycling) is probably not the most likely use of the revenue. ... Using the revenue to reduce a distortionary tax would lower the net cost of a carbon tax by removing inefficiency elsewhere in the economy." (Jorgenson and Wilcoxen 1993, p.20). This is precisely the effect that they find when they reduce distortionary taxes to offset a carbon tax; a 1.7% GDP loss under lump-sum redistribution is converted to a 0.7% loss by reducing labour taxes or to a 1.1% *gain* by reducing capital taxes (Jorgenson and Wilcoxen, 1993, Table 5 p.22). This is an example of where modellers have explored revenue-neutral effective, efficient and equitable policies for mitigation, i.e. experimenting with a wide range of recycling options. Another, even more wide-ranging study of such options was done for New Zealand (Bertram *et al.*, 1993).

The EMF-16 report is published to provide policy-relevant insights on the costs implied by ratification of the Kyoto Protocol, yet the costs (as presented) are almost guaranteed by the lump-sum recycling assumption. The report focuses on how these costs may be reduced by emission-permit trading, but other equally relevant ways of reducing the costs are largely ignored, e.g.

- the more targeted use of revenues and
- the seeking out of opportunities for ancillary benefits, particularly improvements in air quality.

The high costs from the Oxford Model

It is worth examining the origins of the costs given by the Oxford study (Cooper *et al.,* 1999) in detail for two reasons. First, as can be seen from Table 1, these costs are at the extreme top end of the range for the US, Japan and the EU and so represent the worst outcome of adopting the Kyoto targets without a permit trading mechanism in place. The estimated costs appear to rise continuously after 2010 e.g. to 4% of GDP for the USA by 2020. Second, it is the main study in the EMF-16 to consider adjustment costs by combining a global estimated macroeconomic model with an energy model. Weyant and Hill remark that the Oxford model deals "with very important issues not addressed elsewhere in the [Energy Journal] volume", i.e. "macroeconomic adjustment costs" (Weyand and Hill, 1999, p.xiii). Cooper *et al.* assert that "unlike CGE models, *the Oxford model has been subject to statistical verification and so is capable of explaining accurately the historical data*." (Cooper *et al.,* 1999, p.338, italics in original). This makes the study comparable to the EIA 1998

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[1] Reference is made by Weyant and Hill (1999, p. xvii) to the point that the manner in which the carbon tax revenues are recycled will make a difference to the cost results, but that is all. Some of the studies elaborate on the point, e.g. McKibbin *et al.* (1999, p.316-317).

study. In addition, the Oxford model has been extended as part of this study to include an explanation of long-term total factor productivity growth in terms of changes in real energy prices. If the explanation is convincing, it would be a significant improvement in understanding the determinants of long-run economic growth.

The study has its origins in an earlier study on very similar lines released before the climate change negotiations held in Kyoto, December 1997 (Walker *et al.*, 1997). It considers the costs to the world economy of Annex B countries reaching their Kyoto target (1) with carbon taxes (whose revenues are recycled as lump-sum payments to consumers) without the use of the Kyoto flexible mechanisms and (2) with various permit trading schemes. For 2010, the carbon tax scenario gives most of the highest results of all the EMF-16 studies as shown in Table 1. For 2020, it estimates that US GDP is reduced by 4% below the baseline, for a 7% reduction in CO_2 emissions below 1990 levels. This is a striking result in contrast with the EIA result of a reduction of 0.8% of GDP by 2020 for the same 7% reduction in CO_2 emissions below 1990 levels. The contrast is noteworthy because both the DRI and the Oxford models are addressing adjustment costs in a long-term context, with the DRI model assuming a 3-year adjustment period and the Oxford model a 10-year adjustment period.

The high costs in the Oxford results appear to be due to four features in the analysis:

(1) the choice of assumptions;
(2) the level of aggregation of production and the choice of substitution parameters;
(3) the explanation of total factor productivity growth; and
(4) the lump-sum recycling of revenues in a macroeconometric model.

These features are discussed in detail below.

The choice of assumptions
One reason for the high costs of the carbon tax scenario is the adoption of all six worst-case assumptions identified by Repetto and Austin (1997). The six pessimistic assumptions are:

(1) revenues from carbon taxes are recycled as lump-sums;
(2) the results quoted from the Oxford study come from a macroeconometric model rather than a CGE;
(3) there are no ancillary benefits taken into account;
(4) in the results quoted in Table 1 above there is no use of flexible mechanisms of the Kyoto Protocol;
(5) there is no non-carbon backstop fuel; and
(6) no averted climate change damages.

The study reports that Annex B trading in emission permits brings down the costs substantially, e.g. from 1.8% to about 1.0% of GDP in 2010.

The level of aggregation of production and the choice of substitution parameters
The level of aggregation of the production sectors matters in the case of modelling carbon tax effects for the US economy. A higher level of sectoral aggregation of production assumes more homogeneity in production. Since the Oxford model

appears to disaggregate only four sectors (industrial, transport, electricity, and presumably ‘other’), it is not capable of allowing substitution at a more detailed level. However the US economy is particularly well diversified, with advanced non-energy intensive sectors, many of which are among the most dynamic sectors of the world economy, namely, R&D, computing (e.g. internet, software and e-commerce) and many services. In the context of global greenhouse gas mitigation, the US economy is well placed to take advantage of substitution away from carbon-intensive goods and services, but this opportunity is not reflected in the Oxford model.

In addition, the range of fuel substitution possibilities and the values chosen for the parameters affecting substitution will have a critical effect on the costs of mitigation[2]. The long-run price elasticities of energy demand appear to be imposed rather than estimated. The values are –0.5 for the long term (in this study 20 years) for the responses of total use of energy to changes in real energy prices in industry and households and between coal, oil & gas and nuclear/non-fossil fuel use in electricity generation. They are –0.25 for gasoline in transport. These numbers seem arbitrary: it is not explained why they are all the same for every world region, nor why they all appear to adjust at a similar rate from the short run to the long run. Both assumptions, if that is what they are, seem unlikely.

The values also appear to be low compared to estimates in the specialised literature. As an example, take the critical long-run price elasticity of –0.25 for US gasoline demand, implying that if gasoline prices doubled in real terms, then gasoline demand would fall by 25%. This response appears small in the context of a scenario in which the high prices persist for 20 years when both the fuel efficiencies of cars and the mean driving distances can adjust substantially. The literature suggests much higher long-term responses, which make the imposed –0.25 elasticity look biased. For the OECD, cross-section, time-series analyses of road fuel demand either from surveys or from estimated equations suggest a value of –1.12 (Dahl, 1986) or between –0.4 to –1.0 (Johansson and Schipper, 1997), with a best guess by the authors after a review of literature of –0.7. For the US, Franzen and Sterner (1995) suggest an estimate as high as –2.1. Thus this literature suggests an estimate for the long-run price elasticity for US gasoline demand nearly three times the estimate used in the Oxford model.

In addition there appears to be no substitution in the model between fuels with different carbon contents in industry or in households[3]. These can be very important in allowing substitution between coal, oil and gas, which have significantly different carbon contents. Furthermore there is no mention of the development of non-carbon energy sources, such as wind power. A number of such renewable energy technologies are already broadly competitive with fossil-fuel technologies, so that at the levels of carbon taxes envisaged, substantial substitution seems probable. Instead,

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[2] In her foreword to Jorgenson *et al.*, 2000, Eileen Claussen, of the Pew Center on Global Climate Change makes the following remarks. “The most striking conclusion of this work is that the failure to depict the full range of historically-observed substitution possibilities (as many economic models do) can lead to as much as a doubling of the estimated costs of a climate change policy, an overestimate that is wholly attributable to this one pivotal assumption. This overestimation may be even more pronounced since the economy appears more flexible today than in the post-war period when these observations were made.”

[3] Table A1 (Cooper *et al.*, 1999, p. 362) makes no mention of interfuel substitution in these sectors.

the study assumes (p. 349) that marginal abatement costs continue rising and substitution away from coal is increasingly difficult. Also there appears to be no allowance for any development of new technologies such as fuel cells, with much higher efficiencies and different fuel requirements (possibly hydrogen), which may become significant after 2010.

The more substitution that is possible towards lower-carbon-intensive supplies at similar prices to other supplies, the smaller the overall increase in energy prices and the lower the GDP costs.

The explanation of total factor productivity growth

The macroeconomic model includes a supply-side equation explaining potential output in terms of the capital stock, labour supply and a productivity trend. The equation takes the form (Cooper *et al*., 1999, pp. 363-5) of a Cobb-Douglas production function (original notation with all variables in logarithms):

$$Y = \mu k + (1 - \mu)\ell + TREND \tag{1}$$

where Y = potential net output, i.e. GDP,
k = capital stock,
ℓ = labour supply
(when unemployment is at the NAIRU i.e. non-accelerating-inflation-rate),
$TREND$ = total factor productivity trend
μ = parameter.

Consider the effects of rises in real energy costs brought about by a carbon permit scheme. Any consequent fall in potential output, *Y*, is assumed to come from two independent effects: (i) reductions in the long-run desired capital stock, *k*, and (ii) a lowered long-run trend for total factor productivity, *TREND*.

It is a matter of debate whether the desired capital stock in a long-run production function will rise or fall when there is a rise in the relative price of carbon-based energy. *A priori* it seems just as likely that more, rather than less, capital will be needed when carbon-intensive processes and products become more expensive. For example, nuclear energy and wind power would seem to be just as capital intensive as fossil fuel power generation. Although the paper claims that the Oxford model has been subject to statistical verification, the key parameters in this critical area appear to be based on conclusions drawn from empirical studies using data from the 1960s and 1970s (Cooper *et al*., 1999, p. 365).

The assumed reduction in productivity growth when the energy price rises is introduced through an equation:

$$TREND = A + B\,t - S\,rep \tag{2}$$

where t = time trend,
rep = real energy prices and
A, B, S = parameters.

The crucial value for *S* in equation (2) comes from the adoption of an equation given by Marion and Svensson (1986, footnote 12, p.109, notation as used by Cooper *et al.*, 1999):

$$S = E\,(\,Q\,/\,(\,1 - Q\,)\,) \tag{3}$$

where Q = share of energy in total costs
E = the elasticity of substitution between energy and an assumed composite of labour and capital.

An imposed value for *E* is justified by a reference to Lindbeck (1983), who suggested a value of 0.3 to 0.6 for the elasticity is plausible. The higher the absolute value of *E*, the more costly, in terms of GDP loss, is the effect of an increase in relative energy prices, i.e. the effects of a carbon tax. The chosen value for *E* is slightly above the mid-point of Lindbeck's range, i.e. 0.5, and this number appears to be critical in driving the results for the effects of the carbon tax on potential output. Of itself, this assumption implies that for example a 100% increase in real energy prices[4] for the US will lead to a reduction in US potential output of 1.8%[5].

The procedure is suspect on several grounds.

First, the Marion and Svensson (1986) equation is in the context of a global model in which the oil price rises as a result of use of OPEC's market power, rather than as a result of a carbon tax being imposed. However, the oil price change can have a radically different effect on potential output compared to a carbon tax because terms of trade effects become important as prices of oil imports rise. It is not in general valid to transfer theoretical results from a model concerning global oil price changes to one in which carbon tax revenues are received by domestic governments. There are different price responses and substitution possibilities between oil and other energy carriers; and the distribution of revenues is different between countries. However, the Oxford study relies on a result quoted in a footnote[6] rather than the main model developed by Marion and Svensson.

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[4] Industrial energy costs are reported (Cooper *et al.*, p. 349) to rise by 155% for Kyoto emissions targets with a carbon tax and no Annex B trading, but it is not clear if this rise is nominal or real.

[5] This estimate depends on a value share of energy in total costs of 3.4% (1996 US input-output tables) although this share may change as a result of the tax.

[6] Marion and Svensson (1986, p. 109) footnote 12 reads: "Assume that date 1 production of home goods is separable between an aggregate of domestic capital and labor, $v(k, \ell)$ and oil input, z. That is, the production function fulfills $x = f(k, \ell, z) = g(v(k, \ell), z)$. Note that if g(.) and v(.) are constant returns to scale, so is f(.). In particular, with this technology, frequently assumed in the literature, capital, labor and oil are all cooperative in the sense of having positive cross partials."
"With full employment of labor, only x and z vary. By standard results we have $x\hat{} = \theta z\hat{}$ and $z\hat{} = -\gamma q\hat{}$, where x^ denotes the rate of change dx/x, etc., θ is the cost share of oil in the value of output of home goods, and γ (defined positive) is the elasticity of demand for oil with respect to the relative oil price. Furthermore, γ equals $\sigma / (1 - \theta)$, where σ is the elasticity of substitution between oil and the domestic aggregate factor v. Hence, we have $x\hat{} = -[\theta / (1 - \theta)]\, \sigma q\hat{}$, and it follows that for a given oil price increase and a given output level, the absolute response in output is smaller the smaller elasticity of substitution." q^ is the rate of change of oil prices. Note that σ is the short-run elasticity of substitution between oil and the composite good and not the long-run elasticity.

A second reason for questioning the correctness of the procedure is that equation (3) is a result derived by assuming that the economy is in a short-run equilibrium with the capital stock fixed, and labour demand and supply unchanging at full employment levels. The Oxford model is for a long-term outcome with capital and labour varying. The equation as derived by Marion and Svensson (1986) is for the effects of changes in *oil prices on output* rather than in *energy on potential output*. Substituting energy for oil in their equations and using the same notation as equations (1) to (3), their equation becomes:

$$\text{Changes in output} = -\,[\,Q / (1 - Q)\,]\; E\; rep \qquad (4)$$

In equation (4) only output and energy inputs can vary and, critically, *E* the elasticity of substitution between energy and the composite factor (labour and capital) is a *short-run* elasticity. Any possibility of substitution between energy inputs and all other inputs (which are assumed to be fixed) is very limited and *E* is likely to be very small. Cooper *et al.* (1999, p. 365) insert long-run values of *Q* and *E* into the short-run equation (4) and assume that the effects apply to long-run total factor productivity growth in equation (2). This procedure is not justified by the quoted theoretical work. The procedure may bias the results for economic growth downwards because it omits the potential for changes in real energy prices to raise total factor productivity growth through encouraging technical progress.

A third problem concerns the replacement of oil in the Marion and Svensson equation by energy in the Oxford model equation. In the original equation, oil is treated as a primary input (imported) in a theoretical economy with no domestic production of oil. In the Oxford model, the equation becomes, without explanation, an equation relating to real energy use and prices, where energy is produced domestically as well as being imported mostly in the form of oil. The US is the largest oil producer in the world so that one of the basic premises of the original equation (oil as an imported primary factor) is no longer valid (energy is not an imported primary factor but it is a domestic product of labour and capital). An implication of energy being produced is that if the price of energy is increased by a carbon-permit scheme in the US (so that less energy is used) then the resources that would otherwise have been used in producing energy are available for use elsewhere in the economy. For example if less coal is used, then there will be less need for finance of new mining equipment 2010-20. An obvious alternative use of the finance would be for electricity-generating wind farms off the coast or in the deserts of western US. With this substitution (not available in the Marion and Svensson model) long-term productivity growth will not be as depressed as in the Oxford model reformulation.

A fourth problem with the procedure is that equation (3) implies that the higher the substitution elasticity the larger the depressing effect on output. This is the opposite of what might be expected from neoclassical theory in the long run when capital and labour can vary, because normally the more flexible the economy (i.e. the higher the substitution elasticity), the less a shift in relative prices will depress output. This expectation is confirmed by Lindbeck (1983, p. 32) who provides an alternative equation for long-run output growth (notation changed from the original to that of equations (1) to (3)):

$$\text{Changes in output} = -\,rep\;\; (Q/(1-Q))\;\; (1 - (\,0.5\;\; E\;\; rep / (1-Q)\,)\,) \qquad (5)$$

In this equation, output is depressed by the terms of trade effect, but this is offset by substitution away from energy towards labour and capital. This would appear to be a more appropriate equation to explain long-run factor productivity growth, but it has exactly the opposite implications from the equation in the Oxford model. When there are increases in real energy prices, higher substitution elasticities imply higher long-run economic growth rates. In the Oxford formulation of equation (4), higher substitution elasticities imply lower long-run growth rates.

Lump-sum recycling of revenues in a macroeconometric model

Another feature of a macroeconometric model is the inclusion of short-term adjustment of the economy to a shock. If a carbon tax is introduced then what happens to the revenues becomes critical to the short-term outcome (this is not so important in CGE models because the solution is one of long-run equilibrium). Since the rate of the carbon tax appears to rise throughout the period of the simulation, the long-term results will be the outcome of a succession of short-term shocks. The treatment of the effects of lump-sum payments to consumers (the recycling assumption adopted in these studies) will have a major effect on GDP in the years following the tax increase. No details are given. The lump-sum payments become very large, perhaps as much as 10% of consumers' expenditure in the US by 2010. If a significant proportion of the payments are saved, then GDP will tend to fall further and further below the base line as the carbon tax rises more and more to offset the rising demand for carbon-based energy. This appears to go some way to explain the long-term results e.g. US GDP falling further and further below baseline to 4% below by 2020, in contrast with the results from the EIA study (US EIA, 1998) in which the long-term outcome is much more favourable. It seems that the Oxford model has effectively turned a short-term adjustment shock into a larger long-term one, without a coherent and valid justification.

Conclusion

The conclusion is that the high-cost estimates in the literature are either wrong or that they demonstrate:

(1) the costs of making policy mistakes (e.g. by too hasty, unexpected action);
(2) the costs of policies that do not include the use of the Kyoto flexible mechanisms; and/or
(3) how a selection of worst-case assumptions and parameters can accumulate to give high costs.

In particular, the explanation for the high costs in the Oxford results appears to be due to four features in the analysis:

- *the choice of assumptions*. The assumptions used in the Oxford study appear to correspond exactly with those identified by Repetto and Austin (1997) as leading to the most pessimistic outcome for GDP costs for the US. Most of the assumptions hardly seem realistic and could have been predicted to lead to large costs. It seems curious, and not good scientific practice, that they have been made without any explanation or justification, and that no sensitivity analysis has been reported to explore the dependence of the results on the assumptions.

- *the choice of fuel substitution parameters*. The long-run price elasticities of energy demand appear to be imposed at –0.25 or –0.5, without econometric estimation, compared with estimates e.g. of gasoline demand of –0.7 to –2.1 in the literature. Also there appears to be no allowance for substitution between fuels with different carbon contents in transportation, industry or households.
- *the explanation of total factor productivity growth*. This is derived from a short-run equation that is not valid for long-run growth when labour and capital can vary. It imposes high costs of carbon taxation on potential output growth simply by assuming a value for a substitution elasticity picked from the literature.
- *the lump-sum recycling of revenues in a macroeconometric model*. If a carbon tax is introduced in such a model, then what happens to the revenues becomes critical to the short-term outcome. The huge revenues from the carbon tax in the Oxford model are recycled lump-sum to consumers. Insofar as these additions to consumers' income and wealth are largely saved, the economy will become progressively depressed as the carbon tax rises in order to curb the growth in CO_2 emissions.

Taking all the literature into account, the conclusion is that the macroeconomic costs of greenhouse gas mitigation is likely to be insignificant in the US, and indeed in most Annex B economies, provided that the policies are expected, long-term and well-designed. At the same time there are very likely to be large costs for a few sectors, such as coal, and for reasons of equity and political acceptance, compensation of some form in any policy package is justified.

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