Assessment of macro economic transmission mechanisms of carbon constraints through the UK economy

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1. Introduction: Objectives

The objective of this study is to analyse theoretically how carbon budgets (limits on the UK's emissions of carbon dioxide) affect the UK economy at a macroeconomic level. To this end it considers how a range of measures to meet the carbon budgets affect production and consumption in different sectors, and how these changes are transmitted through the economy.

The analysis begins by considering five specific scenarios relating to the introduction of carbon constraints:

1. Imposition of a tax on the emissions of carbon dioxide from certain sectors of the economy;
2. As above, but with a revenue-neutral carbon tax;
3. Regulation to deploy high cost low-carbon technology to achieve carbon dioxide emission reductions, assuming this is more costly or less productive than the current high-carbon alternative;
4. The uptake of energy efficiency improvements which are actually cost-saving;
5. The purchase of "carbon credits" from overseas so as to offset emissions within the UK, and the consequences of funds flowing outside of the UK.

It then proposes empirical or quantitative models that might estimate the macroeconomic implications of each scenario and comments on existing models that are or could be used for this purpose, in particular the Oxford Economic Model, the HMRC model, and the Cambridge Econometrics model. Finally, it concludes with brief remarks about the welfare implications of the carbon emission policies.

2. Five scenarios

Scenario 1: Carbon tax

The introduction of a carbon tax makes energy more expensive. As there are several different types of energy with varying degrees of carbon content, not all sources of energy will be affected similarly by the carbon tax. We can illustrate with an example from the power generation sector, which is an intensive user of energy sources.

The power generation sector employs labour, capital, intermediate goods (which includes electricity), and energy inputs to produce power. The energy inputs are in turn subdivided into those that have high carbon intensity and those with low carbon intensity, which can be used interchangeably. Before the tax is applied, production is via a mix of the two types of energy because power companies have a portfolio of fossil fuels and other generation technologies. In general the high-carbon energy sources are cheaper than the low-carbon ones, reflecting for example the current scenario of coal (higher carbon intensity) being cheaper than gas (lower carbon intensity).

After the tax is applied the cost of all types of fuel increase because none is carbon-free, but low-carbon energy sources become relatively cheaper than the high-carbon ones. The energy mix shifts in favour of more production using low-carbon fuels and overall carbon emissions decrease.

Short term effects (factor substitutions limited and wages sticky)

In the short term, when the tax is applied the production cost of electricity (an intermediate good whose production cost depends on the cost of all inputs, including energy) increases. Switching from high to low carbon fuels (a process known as fuel switching in the electricity generation sector) will offset some of this cost increase, since (for a given carbon tax) the price of the low-carbon fuels would increase by a lower proportion than that of the high-carbon fuels.

Depending on the elasticity of demand for electricity (a function of the extent to which electricity can be substituted for other inputs in production and of the elasticity of final consumer demand), the price of electricity increases and the quantity of electricity used decreases. In the short term there will be little substitution away from electricity use, as demand will be inelastic (for example it will be difficult for firms to substitute other factors for electricity in the short term when they are locked-in to particular technologies and production techniques). Hence the quantity of electricity produced will only reduce slightly, and the price of electricity will increase as the production cost is passed through to prices.

Overall output in the economy decreases as electricity is more expensive. This effect is manifested in two ways:

- aggregate demand will decrease as more income is spent on electricity, leaving less income for other goods;

- aggregate supply will decrease as firms are exposed to an increase in the price of one of their intermediate inputs (electricity), and must increase their prices at any given output level. Resources are now used in producing electricity that were previously available for other production.

In the short term when prices of factors of production are relatively fixed, reduced output and demand mean reduced employment of factors of production across the economy (less capital, labour and intermediate goods).

The overall output drop will not be evenly felt across sectors. For sectors using less electricity, production will not decrease as much as for those using more electricity. The overall demand for labour will drop as production decreases, since the marginal productivity of labour will fall with increased production costs, which will be felt in the short term as a fall in employment as the wage rate is relatively fixed.

Longer term effects (factor substitution and wage flexibility)

In the longer term real wages will fall, which will result in some sectors employing more labour and actually increasing production, as the economy's structure shifts away from energy intensive industry. But as the majority of UK employment (80%) is in less electricity-intensive services, there is likely to be only a fairly marginal adjustment in real wages and minimal impact on labour supply. Those who lose their jobs in the energy-intensive sectors will be a small fraction of overall employment and they will be re-employed elsewhere (or if they are close to retirement retire early).

In addition, assuming no changes to the power generation technology, electricity users will substitute away from electricity – in effect electricity will be more demand-elastic in the longer term. For firms, this substitution process will happen through investment in energy efficiency measures, such as more electricity–efficient machines (this is a substitution of capital for electricity). This shift away from electricity usage will cause production costs to decrease compared to the short term (whilst remaining above the base case). Marginal production costs will fall below prices, so output will increase and prices decrease (depending on the elasticity of the demand curve for this output) until these are equalised again. Similarly, households will undertake more investments in insulation and take other energy-saving measures, thereby substituting away from electricity. Overall they will have more to spend on other goods and services. Hence aggregate demand will increase.

Overall this capital for electricity substitution will to some extent offset the short term fall in aggregate demand, but since the carbon tax will still keep energy prices above the base case, overall aggregate demand will still be lower than the initial level.

In the long term output would still be lower than if the carbon tax had not been applied, assuming that electricity-producing (and electricity-using) firms and households were initially producing and consuming as efficiently as possible, and have been forced to shift to a less productive factor input mix as a result of the carbon tax. [Scenario 4 relaxes this assumption, and explores the effect of increasing energy efficiency in response to a carbon tax which results in a higher overall efficiency.]

The substitution of capital for energy (in this case electricity) in response to an increase in the price of the energy describes the majority of marginal abatement measures in a number of sectors throughout the economy.

Summary of effects

Following the introduction of a carbon tax on the electricity generation sector, we would expect to see the following macroeconomic effects:

- in the short term, when wages are sticky and there are limited opportunities for firms and consumers to substitute other factors for electricity, the price of electricity and all goods using it as a production input will increase, and overall aggregate demand in the economy will decrease, leading to a fall in output and employment. This impact will be felt most by those sectors which are most reliant on electricity as a production input;

- in the longer term, when there is some wage flexibility, employment will recover as wages fall in response to the decreased demand for labour, and output will increase as producers shift production, and consumers shift consumption, so that the economy is less electricity-intensive. Overall long term output would still be lower than if the tax were not applied, as even after other factors have been substituted for electricity, productivity is lower than if the carbon tax had not been applied at all, with prices higher.

Effect of carbon tax on other sectors

The example of power generation serves as a good example of a carbon tax applied to any other carbon-intensive industrial sectors in the economy. The basic process will again be an initial increase in production cost, some or all of which is passed through to the rest of the economy, and a resulting decrease in aggregate demand and supply. Over the longer term a shift to less carbon-intensive production will lower production costs, whilst at the same time unemployed labour will be reemployed as the wage rate falls in response to the initial fall in demand for labour. Hence there will be an increase in output and employment over the longer term compared to the short term, although final output is still expected to be lower than without the carbon tax as the changed production processes are less resource efficient.

Scenario 2: Revenue neutral tax

When the government imposes the tax on carbon emissions it collects some revenue from the private sector. In the discussion of the carbon tax so far we ignored that revenue. As a result we found that overall aggregate demand fell, because companies and the public had to pay higher prices for electricity and other energy sources. But the government has to do something with that revenue. For example, the government may use that revenue to reduce some other, e.g. income, tax, so that the public get back what they have paid in higher energy prices. They will then increase their demand for goods and services, but of course the increase will not be only for energy-intensive goods but for general consumption. Although the additional money they get from the lower taxation is connected to the energy tax, the fact that they get the money back does not make energy cheaper. The money they get back has an income effect on the consumption of all goods according to the income elasticities of each good; the energy tax in addition has a substitution effect against energy-intensive goods.

So when returning the revenue the government restores the level of aggregate demand to its baseline value. But it still creates a switching of consumption, both by companies and householders, away from energy-intensive goods. It also causes distortion to supply decisions – firms in the power sector now choose more expensive (lower carbon) production inputs as do electricity-using industries. This switch to more expensive inputs is the source of the carbon saving. Thus unit output costs rise both because firms now have to pay tax on their inputs and because they use more expensive inputs. Because part of the rise in the prices of electricity and electricity-intense goods is due to higher costs, it cannot be fully compensated by revenue recycling, so there is a reduction in aggregate supply. Of course it is possible that recycling the tax will reduce other distortions and increase aggregate supply elsewhere in the economy. The size of the GDP impact will be determined by the amount of distortion to production (across the economy, including reduced distortions from recycling). Theory cannot tell us the size of the GDP impact, but it is likely to be a GDP reduction because of switching to more expensive inputs.

Similar arguments apply if the tax revenue was returned in the form of more spending, or in the form of transfers to families. The main point is that collecting the revenue in the form of carbon emission taxes and returning it as cash has no aggregate demand implications but causes switches in spending, away from the taxed goods and towards the untaxed ones. Even in an extreme case where the government uses the revenue from the tax to directly subsidise the electricity retail price there will still be an impact on the demand for electricity, because the price will still reflect the changes in the production decisions in the electricity supply industry.

A more exciting use of the revenue from the carbon taxes is one that enhances further the objective of reducing emissions. Firms that succeed in reducing emissions could be rewarded with direct transfers. Firms that invest in energy-efficient technologies could be subsidised. Or the government could use some of the revenue to run campaigns of awareness for the advantages of energy conservation. In all these cases the level of aggregate demand is again unaffected by the tax directly when compared with the baseline scenario, because the tax revenue is returned to the public. But there are further switching incentives, from carbon-intensive goods, inputs and activities to carbon-efficient ones – so the aggregate supply impact, and the emissions saving, is exacerbated.

Scenario 3: Regulated use of more expensive, lower-carbon inputs

There is another way that the government can bring about a revenue-neutral change in the use of carbon-rich inputs, regulation. In this case the government regulates that firms must use a minimum amount of a low-carbon technology in their production and requires firms (and their customers) to bear this cost.

This scenario has a supply-side impact that is comparable to the supply-side impact of a revenue-neutral tax. Electricity-generating firms are legally obliged to adopt more expensive technologies so electricity users face higher costs and alter their production processes. There is an overall reduction in the demand for goods and services that use electricity and a reduction in carbon emissions. With this policy there is no tax revenue to recycle so deadweight losses elsewhere in the economy cannot be targeted as a by-product of the policy. But the reason that economists are critical of this kind of policy is different. There is a distortion from the policy that is uniform across electricity producers and this is not an efficient way to bring about change in the use of inputs. In contrast, the tax increases the price of carbon but lets firms choose how to combine their inputs within the new price regime. Different firms may choose to adopt different technologies, depending on their internal efficiency and their market, so the overall outcome in terms of efficient use of resources is better. In the case of regulation the same restriction is imposed on all producers and what might be good for one producer may be a poor way of bringing about change with another.

This scenario is especially relevant where the government wishes to see particularly expensive technologies introduced that a tax would not necessarily support (e.g. renewables, whose cost per tonne of carbon abated is in many case higher than the expected price of carbon allowances in the EU ETS). The higher the (per unit) cost penalty of deploying the regulated technology the higher the aggregate supply impact and GDP cost will be. Resources will be drawn from elsewhere in the economy to produce the now more expensive electricity, and consumers will have less income left over to spend on other goods.

Scenario 4: Energy-efficient improvements

Our usual assumptions when discussing the implications of government policy for economic behaviour is that both firms and households operate at maximum efficiency. But this may not be the case. For example, the Energy Saving Trust on its website writes that energy-saving lightbulbs "can help you to save money and energy, all in one wise purchase. And by saving energy, you'll be helping to fight climate change too…. just one energy saving lightbulb could save you up to £7 and 26 kilograms of CO2 a year. And because it will last up to 10 times longer than a standard bulb, it could save you around £60 before it needs replacing." Yet, the vast majority of lightbulbs in use are the standard ones.

Companies can also save on carbon emissions by taking up cost-saving energy measures. For example, better insulation can pay for itself in the medium term through energy saving. Some strong campaigns to bring out the benefits of energy saving measures like these can make a difference. More likely, when energy becomes more expensive through the imposition of a carbon tax, companies and households will look for ways to save money. Adopting energy-saving measures is one obvious way. Alternatively regulation can be used to force such changes through more quickly. What does this switching imply for economic activity?

The adoption of energy-efficient improvements reduces the demand for energy so there are now fewer carbon emissions. It also switches some demand from energy-intensive products to energy-saving ones. But as it is likely that the same manufacturers make the two types of products, it is unlikely that this will have much impact on the structure of production. The level of aggregate demand might actually increase from the energy efficient improvements. In the lightbulb example, if each household saves £60 on each lightbulb, replacing ten lightbulbs, the average number in a home, saves £600. This £600 is available to spend elsewhere, so it represents a net increase in the demand for other products, and being an addition to real demand it might have a multiplier effect that can increase its overall impact on the economy.

When firms take up cost-saving efficiency improvements the economic impact is opposite to that outlined for scenario 3 – firms' costs are reduced as they can now produce the same amount with a lower energy input. This will feed through to lower prices and higher output. It will also tend to increase demand for all factors since they are now effectively more productive (this includes demand for energy particularly – the 'rebound' effect). This is akin to an exogenous technology improvement, with the economy now able to produce more from the same inputs and with resources freed to be used elsewhere.

GDP will be increased to the extent of the cost saving. It may rise further to the extent that increased productivity of (and hence returns to) input factors (capital and labour) increases their supply. There may be a further boost to demand in the short-term as resources are demanded for the energy efficiency improvements.

Scenario 5: Carbon credits from overseas

"Carbon credits" are certificates traded in international markets. A firm may buy carbon credits in place of reducing its own emissions, or government may buy credits to help the UK hit a given target. The money to buy the credits has to come from somewhere, such as general tax revenue or through reductions in government spending if bought by government. Taking the money from these sources will reduce domestic aggregate demand, so the policy will have a recessionary impact on the economy. But it will be spread throughout the economy, with no particular impact on energy-intensive production.

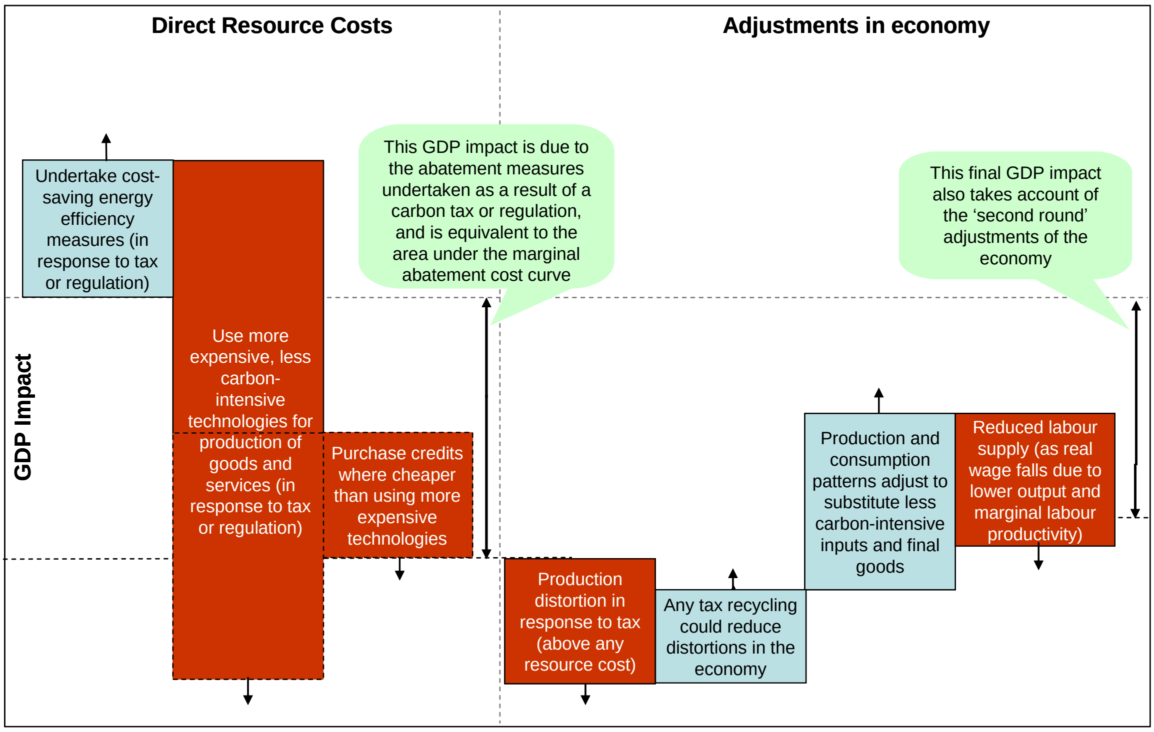
However, the credits will mean that the firm or the UK can make less effort to reach a given target. In fact (under rational decision making) credits will only be bought when they are cheaper than the marginal abatement effort. The cost penalty of buying the credits is less than the cost penalty of using the alternative low-carbon technology (scenario 3), and thus the GDP impact will be lower in the long-run. Where the technology change is simple fuel switching the comparison ends here, since there is no fundamental difference between increased spending on gas in place of coal (with the marginal supply from imports for both) than on credits in addition to coal. Against a technology that places demand on domestic resources however, buying credits may cause a worse GDP impact in the short-run, since the extra spending all goes overseas rather than to domestic factors. The impact on the UK balance of payments and domestic economy from buying the credits is similar to a transfer of money overseas, e.g., by government in the form of foreign aid or by immigrant workers in the form of remittances. Although some adjustment in exchange rates may take place or some of this money may be spent on UK goods, given the UK's share of international trade and the magnitude of UK trade flows, it is unlikely that buying credits overseas will have much impact on the UK balance of payments accounts.

Bringing it together: Carbon Budgets

The carbon budgets will involve a combination of all five scenarios. The majority of ETS revenues will be auctioned by the government, so this effectively acts as an emissions tax on firms in the ETS – scenario 1. However, the government's fiscal rules mean it must balance the budget over the cycle, hence any new revenues will be recycled – scenario 2. At the same time there will be policies directed specifically at deployment of more expensive renewable technologies (e.g. to 15% of UK final energy consumption from renewables under the proposed EU Directive) – scenario 3. The CCC (and many previous studies) have also identified many cost-saving energy efficiency options that government may be able to unlock through regulatory and informational interventions, and that may be taken up in response to carbon pricing and the increased awareness and certainty that carbon budgets will bring – scenario 4. Finally, firms (and government) may choose to buy some emissions allowances and credits from overseas as well as from the UK auction, and are expected to do so where available credits are cheaper than the costs of abating their own emissions – scenario 5.

A theme running through the scenarios above is that the true costs derive from the need to use more resources to deliver a given level of energy services with lower carbon emissions. The subsequent re-optimising of the economy and redeployment of resources away from the more expensive energy input will tend to reduce these costs.

The figure below provides an outline of the different impacts of carbon budgets.



Each rectangle is only intended to show the direction of the impact on GDP, rather than the precise size of the impact.

Considering the Resource Cost (left hand side of the figure):

- Realising cost-saving energy efficiency improvements implies a resource saving;
- Implementing more expensive technologies (in response to taxes or regulations) will increase the resource cost;
- Purchasing credits at a cost lower than that of reducing emissions will reduce the resource cost for a given emissions reduction (but purchasing credits in addition will increase the resource cost in line with the cost of the credits). Clearly if the UK is a net seller of allowances then this will boost GDP.

Considering the adjustments in the economy (right hand side of the figure):

- Insofar as marginal electricity production still involves some carbon its price will increase partly due to the increased resources involved in production and partly due to the tax, which is not a genuine resource cost but a transfer. Responses to the latter represent a distortion and will further reduce GDP. However, in the current situation for the UK, there is emissions trading rather than a tax, so this does not apply[1];
- Auctioning means that emissions permits still imply an increase in revenues to government, and recycling this to reduce distortions elsewhere will reduce costs to the economy;
- The reoptimisation of production and consumption decisions in response to the changes in prices brought about by the technology changes and emissions credit purchases will result in a decrease in the GDP impact;
- Any reduction in labour supply in response to reduced real wages will further reduce GDP. However, given the small scale of any likely reduction and the steepness of labour supply curves, the impact on labour supply is not likely to be large. It is even possible that labour supply may *increase* in response to the measures, since they affect real incomes through increasing the price of a core consumption good – energy – and (marginal) workers may choose to increase their labour to compensate for these costs and maintain living standards. Of course, such an increase, if it takes place, will not be efficient in the economic welfare sense, because it will be induced by distortionary government policy[2].

The balance of effort between extra costs channelled overseas and extra costs spent domestically will affect the short-term impact in particular.

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[1] Any changes in downstream production choices will be an optimal response to genuinely altered resource costs and hence reduce GDP costs. With a shift away from electricity towards other inputs government revenue will be unchanged, since a given number of permits are auctioned, but the UK's net purchase of emissions permits from the EU will be reduced. The value of those permits will be greater than the cost of the distortion to production choices, so the overall impact on GDP will be an increase.

[2] This is in an isolated analysis, on a global, long-term scale of course the change is welfare improving as decisions now reflect the full true costs of polluting goods. Section 5 returns to these issues briefly.

The initial direct resource cost is a first-order estimate of the cost to the economy of carbon budgets - the extra cost of delivering the current level of energy use. In terms of the CCC's analysis this is the area under the marginal abatement cost curve. This will monetise the extra resource cost directly involved. However, the subsequent adjustments to use carbon more efficiently and to buy products that require less carbon input will mean that once the economy has adjusted (in the 'long-term'), the GDP costs will be less than the total of the extra costs implied by summing the extra costs of low-carbon technology and credit purchases.

In the short-term there may be scope for the costs to be higher if resources are under-utilised, however to the extent that carbon budgets can be realised whilst 'moving slowly' and since much deployment of abatement technology will increase spending and demand for resources this effect is likely to be mitigated. The extent to which the longer term costs will fall below the short-run adjustment costs depends on the flexibility of the economy to adapt its capital, technology and consumer choices to the new regime of relative prices for energy.

This analysis has treated the scenarios as if they represent a step change whereas in reality the carbon budgets will imply an ongoing tightening of the UK's carbon emissions until 2050 (and beyond). This could imply that the difference between the long-run and short-run will be limited, with a continuous adjustment going on (much as occurs anyway in any growing open economy). It will therefore not be the case that the impacts will be large in the early years, then fall after a fixed period as the economy reaches equilibrium, but more likely that they will start picking up as the tightening of policy proceeds and eventually peak and fall as the economy adapts to the new regime of low carbon emissions. In a worst case it is feasible that this need to adjust further and more regularly may require a greater spare capacity in the economy and lead to a lower use of resources in equilibrium, but this is likely to be marginal given the size of the affected industries.

3. Modelling techniques

The main objective of the modelling will be to put numbers to the various mechanisms identified in the discussion of the five scenarios. The first scenario involves interactions between factor inputs and spillovers between outputs in different sectors of the economy, and it permeates all other scenarios. For this reason the modelling has to be able to deal with sector interactions. The best-suited class of models for this purpose are the Computable General Equilibrium (CGE) class of models. A CGE model defines several sectors of the economy as different entities that interact with each other through input-output links. The model's equations are derived from maximization at the micro level, so the parameters in the equations are structural parameters independent of policy. A CGE model is an equilibrium model in the sense that the demand and supply of each good and factor of production derived from the micro maximization are equal to each other.

1. CGE models have several advantages over estimated macroeconomic models (to which I will return to discuss further in section 4 in reference to the Cambridge Econometrics model). Macroeconomic models are by necessity aggregate models of the economy, but a carbon emissions policy has different impacts on different sectors of the economy. More importantly, the equations estimated in macroeconomic models may not be invariant to the policy options being studied (they are subject to the "Lucas critique"). Of course, CGE models are more difficult to solve but with the current state of knowledge they are the only models that can deal simultaneously with all the sector interactions induced by carbon taxes. This is especially so when the objective is to derive the long-run (equilibrium) effects of an abatement policy, when the solution of the models is also more manageable.
2. In cases where there is also interest in short-run adjustment dynamics and out-of-equilibrium behaviour CGE models are considerably more difficult to solve. Some allowance for slow adjustment to equilibrium can be made but a single CGE model will not be able to deal with all the cases discussed under the five scenarios. I first outline the structure of a CGE model that can be applied to the study of carbon emissions and then explain how the five scenarios fit into the model, when they do.

Structure of the model

At the risk of oversimplification, a CGE model needs to have a demand equation and a supply equation for each good. Ideally each should be derived from maximizing models with deep policy-invariant parameters. This is not always feasible, however, especially when it comes to foreign demands, and short-cuts are available.

1. The demand for a good comes from two sources, final demand from utility maximization given prices and consumer incomes, and intermediate demand from profit maximization by firms. In the open economy the demand for each good also has a foreign component. In a pure CGE model these demands are derived from utility maximization, with the utility function defined over domestic and foreign goods. Because of the nature of the problem, however, it simplifies the model substantially if instead of deriving demands from utility maximization for the domestic and foreign economies a demand equation is written down for each sector's output in terms of the sector's relative price (inclusive of VAT), the economy-wide terms of trade (or sector-specific ones

where data are available) and domestic and foreign disposable national incomes. Foreign national incomes should be the average national income of the trading partners with weights equal to export shares. These demand equations can be of one of the simple types derived from systems of demand equations, such as the linear expenditure system, or estimated from panels of econometric time series (although this task is not easy – estimated demand elasticities in the literature vary a lot when there is disaggregation across sectors).

2. The second component of demand for the output of each sector is demand by other production units. The underlying assumption here is that each industrial sector has one representative firm and so input-output tables for industrial sectors can be used to find the connections between the sectors. A demand equation for each sector is obtained for intermediate goods (see below) and then this demand is allocated across the other sectors' outputs according to the input-output weights.
3. Finally, there is demand for goods by the government which is taken as exogenous. A variety of assumptions can be made about government demand responses to changes in carbon prices but none of them can yet be derived from an economic model. The assumptions can be dictated by policy and government targets.
4. The key side of a CGE model targeted to the analysis of carbon emissions is the supply side. Production takes place in a number of industrial sectors, which for practical reasons may have to be at the 2-digit industrial classification level. For the study of carbon emissions the model needs at least four factor inputs, labour, capital, intermediate goods and energy. These could further be subdivided into other inputs, which may be important for energy if different policies apply to different types of energy inputs.
5. In general the production function for each sector gives output as a function of the four inputs. But because substitution possibilities may differ between any pairing of factors, the substitution possibilities between factors are described by a nested CES structure. It is likely that capital is a better substitute for energy, so one may write sub-production functions, starting from the lowest level, as follows: a CES function giving substitution possibilities between capital and energy; next a CES function giving substitution possibilities between the "output" of the first function and one other input, preferably intermediate goods; and finally a CES function of the output of the preceding level and the labour input. The three substitution elasticities then determine the price elasticities of demand for each factor. Prices are taken as given by the firm. Of course, other substitution structures are possible, for example, one may assume that intermediate goods and energy are closer substitutes than capital goods and energy are.
6. The demand functions for factors are obtained from profit maximization at the sector level, given the output price and the prices of factors of production. The simplest way to solve the model is period by period, by solving for the static maximization conditions for each factor. The period-by-period solution gives the long run impact of emission taxes, which might need, say, ten years or more to materialise. This solution method may also be appropriate for intermediate goods and energy in the short and medium runs, because the firm can change the quantity of inputs for these two factors without time delay. But it is not appropriate for capital or, in some circumstances, for labour in the

short and medium runs. For capital something needs to be done about its sectoral specificity and the costs of switching types of capital goods. For labour the question is how mobile labour is across sectors in response to any structural change that might come about after the change in emissions policy.

7. The modelling of the demand for capital can follow one of two approaches. One is the vintage approach, followed by the MIT EPPA model. Capital is divided into a number of vintages, in the EPPA model four, and older vintages are replaced first. A vintage is defined by the timing of the investment that led to the capital accumulation. However, given the arbitrariness involved in defining the vintages, the second approach that defines quadratic costs of adjustment seems more practical. It is more straightforward to implement and at least at the aggregate level we know enough about costs of adjustment to calibrate the model. Quadratic costs of adjustment work well at the aggregate level and they should also work well for sectors with high capital intensity. For this reason it might be appropriate to assume quadratic costs of adjustment for manufacturing sectors and solve demand for capital in the rest of the model period by period. (The vintage approach has the advantage that capital scrapping can be endogenized, in the sense that the speed at which older vintages are replaced can be endogenous to the model. But there is a lot of arbitrariness in choosing the replacement rates that in my opinion do not make it worthwhile adopting this approach.)
8. For employment there are potentially lags in both the demand and supply side. On the demand side the lags are similar to capital. In service sectors they may be longer than the capital adjustment lags. For example, it may take longer to find a good employee to fill a vacancy than it does to replace the office computer. However, these lags are not likely to be important in the context of carbon emissions policies. The labour lags that are likely to be more important, if at all, are the ones derived from the speed at which workers can change jobs, especially jobs that are located in different sectors of economic activity. Whatever the source of the lags, the modelling here has to be reduced-form, in the sense that dynamic supply equations are written for each sector. The rate at which labour moves into a sector is given by the relative size of the sector (its share of employment) and its relative wage, where the relative wage is given by the marginal product of labour in each sector.
9. This still leaves open the question of unemployment and the question of the supply (participation) elasticities. CGE models with unemployment exist in the macro literature and use the search approach. Namely, they assume that there are frictions in job change, so when workers lose jobs in one sector it takes them time to find a job in another. I do not think the complexity of introducing this type of market imperfection is worthwhile in the context of carbon emissions policies (although it is feasible). The impact of these policies on employment is small and it can be calculated from models that assume that labour is fully employed until it moves in response to the wage differential. Once the path of employment adjustment is calculated it is possible to deduce heuristically the likely path of unemployment, which is usually proportional to the required employment adjustment.
10. With the aggregate labour supply one may assume that when wages fall in response to the emissions tax, some workers leave the labour market according to a pre-determined elasticity of supply. This supply elasticity varies a lot across demographic groups, being higher for older workers than younger ones

and higher for women than men. It is not feasible for a macro model geared to the impact of an emissions tax to distinguish between different demographic groups at the same time. The additional complexity does not justify the likely payoffs. But the different supply elasticities should be borne in mind when discussing the results.

11. Profit maximization subject to the production technology and prices of inputs and output gives the demand for each factor of production. The demand for intermediate inputs and investment become demand for the outputs of other sectors of the economy thus providing the linkages between sectors in the economic system. Note that service sectors also produce a large fraction of intermediate goods so these linkages involve service sectors as producers. Equating demand and supply for each sector gives the equilibrium prices for all goods and factors with some factor prices given from abroad. Raw materials such as oil are the main examples of such goods.
12. There remains the question of macro variables needed to close the model, in particular the real interest rate and the government budget. One could assume a Taylor rule for the interest rate with an independent monetary policy but to do this the model needs to have inflation in it as an endogenous variable and an output gap. CGE models with price stickiness and a Taylor rule have become popular tools for analysing the impact of nominal and real shocks on the economy, and generally perform well. But these models are aggregate and assume price stickiness at the aggregate level. It is not feasible at present to write models with many sectors and different degrees of price stickiness in each sector, as would be required in a CGE model designed to capture the impact of emissions taxes on the real economy. It seems that the assumption of a constant interest rate in a disaggregated model is a convenient and most likely innocuous simplification in the analysis of the impact of carbon taxes on the economy.
13. The government budget also needs to be specified, especially as it relates to the analysis of the recycling of the carbon tax revenue. There are two ways that this can be done, given that the focus of the model is not on the impact of fiscal policy. The first is to introduce the main government instruments as exogenous variables and not be concerned about the balancing of the budget. The second is to introduce the government budget equation and assume that one of the instruments, usually one of the expenditure items, acts as the residual that balances the budget. The former seems to be preferable in this case because of its simplicity. I will return to this question below when discussing the way that the five scenarios can be modelled.
14. Three types of taxes need to be distinguished, VAT, income tax and payroll tax, and introduced into the model at the relevant stages. The VAT rate should be added on to the price of final output, the average rate of income tax on to wages and capital income, and the average payroll tax on to the wage costs of firms. Government purchases of goods and services are distributed across industrial sectors according to historical data and transfers are added to consumer incomes.

The five scenarios in the model

1. Scenario 1 is the easiest one to deal with within the model. Since energy is a separate factor of production, one unit of it will have some price *p.* Say that for some industry the energy input is such that it emits *x* tonnes of carbon

when used in production. Then the price of the energy after the tax is $(1+xt)p$. The x will vary across sectors depending on their carbon intensity. A CGE model will then be able to trace the impact of t both on the sector and on the economy as a whole.

2. Scenario 2 retains the taxes of scenario 1 but then returns the revenue. To deal with this a balanced budget equation is written for the carbon taxes, with unknown the tax or expenditure item that is adjusted in response to the bigger emissions revenue. For example, if the carbon tax revenue is returned in the form of lower VAT rate, it is worked out how much the VAT rate needs to fall to exhaust the carbon tax revenue and this reduction fed into the model. Alternatively, if the revenue from the tax is returned to firms as a reward for cutting emissions, a new instrument needs to be introduced, which is a subsidy that is proportional to the fall in the emissions between one period and the next. The level of this instrument is calculated from an equation with the carbon tax revenue on the right hand side.
3. In scenario 3 the firm adopts a high cost low carbon technology. This case cannot be analysed within the framework of conventional CGE models because an assumption needs to be made about the source of the new technology. Technology in CGE models is described by a CES function with fixed shares parameters of factors. The new technology will presumably have different share parameters, most likely lower ones for energy inputs, and higher ones for other inputs. But the values of the new parameters cannot be known if the new technology is genuinely new and not previously used. The only suggestion that can be made here is to introduce assumptions about the alternative technology based on a priori beliefs and experiment by adjusting the model's parameters accordingly.
4. The adoption of new technology will also mean lower carbon content of energy. This part can easily be calibrated by a change in the x of scenario 1.
5. As with scenario 3, energy efficient improvements in scenario 4 cannot be shown at the level of the firm or the household because they are outside the normal production structure. But they can be brought into the model as a further component of the demand for carbon energy through an independent demand equation for energy, with an appropriately chosen price elasticity. The tax increases the price of energy and this causes a fall in this type of demand for energy, which is then used in conjunction with the other impacts of the tax to calculate the overall effect. The demand equation can also be shifted exogenously in response to an emissions awareness campaign.
6. The quantitative questions are first how big should the price elasticity of this type of demand be, and how large should be the exogenous shift in response to an awareness campaign? The price elasticity in this demand equation is due only to the saving from energy-efficient improvements so it is less than the estimated elasticity from a reduced form demand equation for energy. But if one could identify how much the "wasteful" energy demand is, the price elasticity on this component of energy demand might well be higher than the average elasticity of reduced form equations. There is obviously some arbitrariness here but alternative elasticity values can be tried depending on prior beliefs. Similar remarks apply to the question of the shifts in the demand for energy due to awareness campaigns.
7. Carbon credits from overseas can easily be incorporated into a CGE model. They play the role of the tax in scenario 1 when they are paid by the firm or

paid by the government out of the tax revenue collected from firms. Instead of a tax t we use the price of a credit for one tonne of carbon emissions. If the government pays out of the general budget they do not have an impact on the individual firms, they are instead added to exogenous “wasteful” government spending (i.e., government spending that does not buy anything from producers). In the case where the government budget equation is not specified this type of government spending is simply ignored.

4. Commentary on some models

The Oxford Economics model

Oxford Economics (OE) uses two models to make predictions about energy use. The first model is a CGE model of 30 sectors at the two-digit industry level. It was developed by OE for the analysis of energy markets, with acronym OEIM. The second model is a conventional econometric model of the aggregate economy, the Global Macroeconomic Model (GMM), also developed by OE, characterized by an array of conventional short-run (Keynesian) rigidities.

In the OEIM each industry has a production function of four inputs, capital, labour, intermediate goods and energy. Each industry's intermediate inputs are the outputs of other industries. The links are obtained from input-output tables. The exogenous variables are the prices of the factors of production, except for labour. For labour the exogenous variable is the aggregate supply of labour (employment). The endogenous variables are the quantity of inputs, the outputs, the prices of outputs and wages. To compute prices the model has demand equations for the output of each sector, made up of domestic consumption demand, domestic industry demand and foreign demand. This is a short cut, since a fully-fledged CGE model should define the utility function and the demand equations should be in terms of the preference parameters rather than final elasticities. It seems, however, adequate to write the reduced forms when the main interest is in the supply-side substitutions. When the value-added of each and every sector are added together the model delivers aggregate GDP. The model is a long-run equilibrium one, in the sense that the impact from a change in prices on each one of the quantities is the eventual impact that is obtained when all short-run adjustments have taken place and when the balance sheet constraints in the economy are satisfied.

In order to derive the short-run dynamics, the computed change in GDP from the OEIM model is entered as an immediate and permanent fall in potential GDP in the UK components of the GMM, a standard aggregative (Keynesian) model of the UK economy. This opens a gap between actual and potential output which sets in motion short run price and wage dynamics and which eventually get the economy on to a new equilibrium, with the lower level of output and whatever else needs to adjust. However, employment is unchanged in the long run and there are only small adjustments to the capital stock, so the brunt of the adjustment in GMM is in TFP. In the context of the GMM model this is equivalent to an exogenous downward shift of the aggregate production function. This is acceptable if GMM, as I suspect, has only two factors of production, labour and capital, as in this case all non-capital inputs like energy are bundled into TFP.

More recently, OE introduced some modifications to the CGE model to take into account more short-run adjustments. This change was partly in response to comments by OXERA in 2006. The modifications are as follows.

First, a measure that is not so much about short-run adjustments but about additional savings related to "conservation". This is the idea that both companies and households may take measures to save energy once and for all at the beginning of the anti-emissions policy and once the conservation is made it continues under all scenarios. This idea is close to scenario 4 above, of energy efficient improvements.

The savings were apparently suggested to OE by Defra. As suspected in the discussion of scenario 4 above, this modification does not contribute much to GDP.

Second, the OE model distinguishes two types of capital stock, normal and energy-saving. In this modification it is assumed that there is faster scrapping of normal capital and substitution with energy-saving capital. It corresponds roughly to scenario 3. When this modification is introduced the OEIM model implies a faster adjustment to the long-run equilibrium, in the sense that the faster substitution in favour of energy-saving capital reduces energy use faster in the short term.

Finally, it is assumed that there are impacts on TFP, the total factor productivity in the economy as a whole. When the price of energy rises the productivity of capital and labour fall at given energy use. As new technology is adopted that economises on energy use, productivity recovers somewhat. In this extension to the model TFP recovers by more, under the plausible assumption that other technological improvements not associated with the quantity of energy use also improve capital and labour productivity.

Comments

Overall: the OE approach is a reasonable compromise between the need to study abatement policies within the context of a multi-sector model and the desire to trace the adjustment paths of the endogenous variables to their new equilibrium values. The CGE model is sufficiently disaggregated to deal with the interactions of sectors and derive long-run equilibrium impacts. The production structure is not as rich as in current CGE models (the nested CES approach offers more flexibility than the Cobb-Douglas and linear approach mostly followed by OE). The short-run adjustments in each sector of the economy mimic the aggregate dynamics and this is a problem (see also below). More could be done with costs of adjustment for capital and perhaps also for labour, especially in the most offending heavy manufacturing sectors.

More specifically:

1. The OEIM model is one for computing the equilibrium effects of changes in energy prices. Normally, changes in energy prices would have an impact on the prices of other factors of production, as well as on the quantity of inputs. This is especially true for wages and employment. The impact of energy prices on equilibrium GDP, and especially on its adjustment to its new equilibrium level, partly depend on what happens to wages in response to the price change. There is a parallel here with the lessons learned from the oil price shocks of the 1970s. A common theme in the macro literature is that the impact of oil price shocks on the European economies was more damaging than on the United States economy because US wages adjusted fast whereas European ones were more sticky. OEIM follows an extreme version of this split of the adjustment in the prices and quantities of inputs: all adjustment in capital and the intermediate goods that are not produced domestically is on the quantity, and all adjustments in labour is on wages. The calculated impact of the emissions tax on GDP is lower by the assumption that labour bears all the costs of the tax through lower wages without a long-term supply response (although the GMM does show the economy-average employment response in the short-term). It is also lower when there are other factor prices that do not rise but given that the main other price that does not rise is the price of capital this is not implausible, as we also pointed out above.
2. Putting to one side for the moment the recent modifications to OEIM, the short run adjustments in the OE simulations are determined entirely by the rigidities

in the aggregate GMM model. The shock introduced into the GMM model is a fall in potential GDP and the macro rigidities give a path for actual GDP from its current level to the lower level in 2020. The adjustment path is what one would expect, a gradual fall with cycles. Given now an adjustment path for GDP, one can go back to the OEIM model and allocate the period-by-period GDP reduction to each sector according to their long-run contributions to the fall in GDP. So wages and employment at the economy-wide level are allowed to respond to the energy price rise in the sort-run adjustment.

3. It is a little far-fetched to claim that each and every sector in the economy is subject to the same short-run frictions and rigidities as the average of the economy as a whole, so the economy-wide adjustment cannot be used as an indication of the adjustments in individual sectors. Normally manufacturing sectors, especially the ones that are more energy-intensive such as basic metals, have longer adjustment lags, than, say, financial services. When carbon prices rise the inability of the energy-intensive sectors to adjust fast could cause bigger short-run problems than the ones derived in the OE simulations. The introduction of sector-specific costs of adjustment should deal with this problem.
4. The use of an aggregate model to predict the adjustment lags is also subject to the criticism that the adjustment lags associated with the structural change that follows the carbon emissions policy are missed altogether. Making energy more expensive should reduce the share of the energy-intensive sectors in both aggregate value-added and employment. This reallocation will take time, irrespective to what happens to aggregate GDP. How fast does employment move from the manufacturing to the service sectors as a result of the policy change? History shows that this adjustment is slow and might cause a further short-run recession that lasts 4-5 years. There might also be some retirement of older workers employed in the heavy manufacturing sectors. These factors may suggest that the macro level adjustments to carbon taxes are longer and more drawn out than currently incorporated in the GMM, and additional research should validate the lags included in the GMM.
5. The recent adjustments to the OEIM are designed to deal with the problem of the one-size-fits-all approach of the GMM model. They are superimposed on the model to deal with this particular issue and not derived from the same framework as the rest of the model. OE make plausible assumptions about the various effects that they discuss but the results are sensitive to assumptions made on the basis of intuition and plausibility rather than hard econometric evidence. The predictions made are useful as indications of where the short-run dynamics might deviate from the ones obtained from GMM, but I would not place too much confidence on the exact numbers reported. This is especially true of the second modification which is by far the most important one in the simulations, the substitution towards energy-saving capital. The assumptions that have to be made to obtain this estimate were based on detailed MARKAL modelling, but the number of uncertainties involved mean that the results should be treated with caution.

The HMRC model

The HMRC model is a CGE model designed to simulate the impact of tax changes. It is much richer in the specification of tax and spending instruments than needed in a

CGE energy model and not rich enough in its industry structure. There are obviously good reasons for this emphasis. If HMRC is to be used for the study of the impact of energy taxes it needs to be simplified in some directions and expanded in others.

The model has 11 industrial sectors producing differentiated goods and 45 households, and is solved over a 45 period horizon. The period can be a year, so this is a good horizon length. The links between the periods are given by household expectations and asset accumulation and by capital, which is subject to costs of adjustment. The model is solved simultaneously over the 45-period horizon rather than period by period. Household demand functions for each good are derived from a Stone-Geary utility function with a minimum subsistence level and Cobb-Douglas preferences over and above that level. This gives rise to a linear expenditure system with the elasticities for each good obtained from econometric estimates.

1. It is not completely clear why the number of households is set at 45 and what is the significance of differentiation between households. It may have to do with the computational requirements but it would appear that a single "representative" household assumption, or a reduced form linear expenditure demand equation for each good, would produce the same results. Especially in the model for energy use, where the emphasis needs to be on the supply side, the assumption of a single linear expenditure equation for each good, including energy, would serve the model well.
2. Industries are monopolistic competitors, which is a good assumption although for the impact of energy taxes it would probably yield the same results as the assumption of perfect competitor firms and market clearing. There are fixed costs of firm entry and free entry subject to those costs, and investment is subject to quadratic costs of adjustment. Firms choose their adjustment paths over the entire horizon under rational expectations. A novel feature of the model is that there is interaction between households' maximising decisions with respect to savings and consumption and firm's maximising decisions with respect to investment. These are all very god features for a CGE model with short run adjustments.
3. In the description of the model in the paper by Adam Blake and Jonathan Gillham that I was given it is stated that output is a fixed coefficients (Leontief) function of value added and intermediate inputs, so the ratio of intermediate inputs to other production functions is fixed. This is obviously an unsatisfactory assumption for the analysis of carbon taxes. It eliminates the main channel through which taxes on energy will have an impact on the firm. However, in subsequent conversations and a summary of the assumptions of the model that I was sent it is stated, without more details, that production follows a nested CES structure. If the CES structure extends to energy it is clearly a vast improvement and the most that can be hoped for from a CGE model.
4. Government is specified in some detail given that this is a model designed to study the impact of general government tax policy. Again, there is a difference between the assumptions in the paper description of the model and the assumptions in the subsequent document. In the Blake-Gillham paper version the income tax rate is endogenous and accommodates any changes in revenue and government expenditure. Government expenditure and other tax rates are exogenous. In the more recent version all tax rates are assumed exogenous except for the corporation tax, which is derived endogenously from the

financing decision of the firm. This, again, is a much better assumption with regard to the treatment of energy taxes than the earlier alternative.

5. Finally, the foreign sector is modelled by assuming flexible exchange rates and imperfectly substitutable domestic and foreign goods, which is standard practice in modern trade theory.
6. Overall, the HMRC model has many desirable features of modern CGE models. In particular, the demand side of the model is richer than the Oxford Economics model and derived from a well specified utility maximization structure. Government is also modelled in more detail, although this detail is probably not adding much to the analysis of carbon policies. Where the model needs to be expanded is in the number of industrial sectors used, in the number of factors of production and in the substitution possibilities between factors and intermediate goods. Energy needs to be distinguished as a separate intermediate input and the composition of the energy input for each sector needs to be specified separately.

The Cambridge Multisector Dynamic Model (MDM-E3)

The economic model

The Cambridge Multisector Dynamic Model of the UK economy (MDM-E3) grew out of the tradition of aggregative Keynesian (demand-driven) econometric modelling of the UK economy and to some extent reflects that provenance. But it would be unrecognisable to Keynesian macroeconomic modellers in a number of important dimensions. It still makes extensive use of co-integrating time-series econometric estimation but mostly at the sectoral and regional level, treated as panel data allowing for all sectoral and regional fixed effects. It also makes use of input-output matrices to model the commodity flows necessary as part of a consistent treatment of the demand for and supply of products. In MDM-E3 the macroeconomic results emerge as the summation of results at the sectoral level. The energy sector is modelled in detail to trace the substitutions between different fuel types and energy use. The techniques used in the energy sector are a combination of time-series relationships and cost-minimisation in the choice of fuel types to produce energy.

The core structure of the model is the use-of-output equation (aggregate demand), which gives domestic output as the sum of household consumption, government consumption, fixed investment, inventory investment, intermediate goods, exports and net of imports. Each component is modelled separately. Household consumption is broken down into 51 different categories. The demand for each is estimated separately as a time series regression with independent variables household disposable income, the relative price of the category and dependency ratios. Government consumption is exogenous and is again divided into a number of categories. Fixed and inventory investments are divided between 27 investing industries, and a time series regression is run for each, with independent variable the relevant sector output. Exports and imports are estimated by industrial sector with competitiveness as an additional explanatory variable. Intermediate demands (except for energy) are calculated from input-output tables, given the output of each sector. For example if in order to produce a unit of output a sector requires x units of the output of another sector as intermediate goods, a policy that increases the output of the buying sector by one unit will lead to the prediction that the demand for the intermediate good will increase by x units.

The number of product categories and sectors has been chosen to reflect the key differences of interest among sectors in the economy. Thus, although the data would permit greater disaggregation within manufacturing, the sectors concerned are now small and distinguishing them would offer little gain in understanding. An identical classification is followed in the European (E3ME) and global (E3MG) models also developed and maintained in Cambridge, to permit comparison and the use of outputs from one model as inputs to another, where desired. The estimation is annual and most time series are available from 1971 or earlier years, sometimes back to 1954. From the National Accounts identity, gross output for each sector is the sum of intermediate demand, value added and taxes and subsidies on production. Intermediate demand is known from the input-output tables, taxes and subsidies on production are calculated by the application of tax rates to a relevant tax base and so the identity can be used to obtain value added in each sector. For the current price variables, wages (strictly compensation of employees) is determined as the product of employment and average earnings, for both of which there are sets of econometric equations. Profits, including depreciation, are then derived as the residual from value added. The incomes thus generated in production are allocated to different institutions including households which gives household incomes, which feed back to the household demand equations.

Employment in each sector is obtained from another set of econometric regressions that run employment as a function of sector gross output, real product wages and unemployment rates. Prices are obtained as econometric equations which include as explanatory variables unit output costs, the price of competing imports, and a "technology" variable to pick up the impact of changes in quality on prices.

To illustrate how the core of the model works, suppose there is an increase in some tax, e.g., the income tax rate. In the first instance this reduces household disposable incomes, and through the demand equations, it reduces sectoral demands. Through the input-output tables this also reduces intermediate demands and through the investment equations and import equations it also reduces output, investment and imports. Each sector's gross output is now lower depending mainly on the income elasticity for each sector's output. With lower gross output wages, profits and so household incomes are lower still, creating a "multiplier" effect that feeds back into the output equations. The lower output also has an impact on employment through the employment-output equations. The lower employment leads to higher unemployment, which affects the labour supply via participation equations, and lower price inflation, via the price equations. Both responses introduce negative feed-backs into the system and reduce the initial effects of the tax increases.

As already pointed out, the model is multi-sector and the links between sectors are picked up from the input-output tables. But as the previous illustration makes clear the model is still essentially Keynesian in character. For example, the initial impact of a tax on output is through the household demand equations and neither labour supply nor the capital stock (e.g., through a production function) play an explicit role in the determination of output and employment, except that higher unemployment has a moderating effect on wages which stimulates both employment and output (through improved competitiveness). There is no assumption that factors of production will be fully utilised in either the short or long run. The way that the model avoids a large and potentially unreasonable impact of a policy change such as a rise in income tax is through the recycling of revenue. For example, in the previous example, if the revenue from the income tax is spent by the government, the fall in household demands is offset by the rise in government spending in the gross output equations. The main impact of the policy is then to redistribute investment and employment from the sectors that have a high income elasticity for the demand for their product to the sectors that attract government expenditure.

Modelling Energy

The model estimates demand for energy and fuel for each fuel user and models the end-user fuel prices. The model distinguishes 13 different energy users. The first three are power generation, which is modelled using a separate electricity supply sub-model and fed into the energy sub-model. The electricity supply sub-model uses a 'bottom up' approach. Transformation of energy (such as oil refineries) and energy own-use by the energy industry. The energy needs of the last two sectors are obtained from accounting matrices. The requirements of the other ten sectors are modelled as final-demand time series and estimated using the time series (cointegration) techniques of the economic model, with independent variables the output of the sector (or in the case of households total expenditure), a technology variable, air temperature and the relative price of energy.

The aggregate demand for energy obtained from the 13 sectors is shared among twelve different energy types (of which the main ones are electricity, two solid fuels, three oil-based fuels, natural gas, purchased heat, biofuels, and combustible waste) according to a new set of econometric equations. The dependent variable in these is the share of each fuel type and the independent variables a measure of aggregate activity, the relative prices of the energy types, technology and temperature. The result is the demand for energy, by fuel, in physical units, for each fuel user.

The fuel use by user obtained from the energy sub-model is used in the economic model to calculate a new set of input-output coefficients for fuel products on the classification in the economic accounts (coal, manufactured fuels, electricity and gas supply). With these coefficients it is then possible to calculate the purchases of fuels by industry. For example, if a tax is imposed on a type of energy, the energy sub-model will estimate how big is the impact of this tax on the fuel type in question and on other fuel types, and on each fuel user's total energy use. If, as expected, demand for the fuel that is taxed falls and demand for the other fuel types rises, the estimates yield a new set of input-output coefficients for fuel commodities, which are then used to forecast the change in industry purchases of energy products, so that the economic accounting is consistent with the energy sub-model's accounting in physical units. The resulting impact on industry prices and competitiveness in turn feeds through to industry output, and this is again fed back on to the energy sub-model, and so on until convergence is reached in solution. The result is the overall impact of the tax on both final output and factor substitutions.

Related to this, the Cambridge Centre for Climate Change Mitigation Research is also developing a model of demand for appliances by households in response to changes in technology and relative prices of fuel types.

The electricity supply sub-model

The electricity supply sub-model is essentially a model of the demand for energy types by the electricity industry given current load factors and optimal load factors (when electricity demand changes) for existing and potential generating plants. The model has two components. In the first, the optimal mix of fuel types is obtained given existing capacity, the prices of fuels and carbon, optimum and maximum load factors,. Then, given any constraints on load factors and the renewables obligation, optimal fuel demands are obtained given the electricity requirement. Optimality here corresponds to the minimum cost combination of fuel inputs.

The second component is derived from the Energy Technology Model of Anderson and Winne and its aim is to pick up changes in overall generation capacity and of individual generation technologies, including renewables. Given current and extrapolated demand for electricity, the model derives investments in different technology types and capacity requirements. again in light of the same factors mentioned above, though future fuel, carbon and RO prices, and capital and operating costs are considered as well. Optimality here corresponds to the minimisation of cost. The electricity sub-model gives electricity prices and optimal demands for different fuel types. These are fed on to the economic model and the energy sub-model and a new demand for electricity and other fuels is generated, which feeds back on to the electricity sub-model.

Emissions

Cambridge Econometrics has computed a matrix of coefficients for the emissions of each fuel type, based on the National Atmospheric Emissions Inventory (NAEI). So the way that, say, taxes on emissions could be modelled is to use the matrix of coefficients and calculate an effective tax rate for each fuel type, based on their emissions.

Summary

The energy and electricity sub-models contain a lot of detail about different fuels, and power generation technologies. They obtain the demand for each different fuel type and the implications for emissions from models that combine time-series estimation with minimum-cost calculations, given industry and household requirements obtained from the economic model. There is then interaction between the economic model and the energy sub-models according to which higher costs in the energy sub-model feed as higher energy prices in the economic model, which in turn give lower industry or household activity. Lower activity feeds back into the energy model and reduces the demand for fuel.

Evaluation

The MDM-E3 model is a comprehensive model of the UK economy, with emphasis on Keynesian-type demand dynamics. This contrasts with the price dynamics and market clearing of CGE models. The model has relative-price effects, especially in the energy sub-model and trade equations, but the main driving forces are the outputs of each sector and the disposable income of households. Take as an example the tax on carbon emissions of scenario 1. The impact of the higher price of carbon on the net price of each energy type is calculated from the matrix of coefficients that give the carbon emissions of each fuel type. Given the higher cost of the different fuel types, the electricity supply model gives the impact on the cost-minimising demand for each fuel, conditional on electricity output, and the energy sub-model gives the impact on final sector demands for the fuel types. These in turn yield adjustments to the input-output coefficients that link industry outputs with the outputs of the energy industry and through these adjustments the economic model gives a new set of factor demands and output supplies for each sector. In a second round these are fed into the energy and electricity supply sub-models until the model converges to a final set of demand and supply for each factor of production and each sector output.

The model reaches "equilibrium" following a tax change in the econometric sense of convergence of all equations and consistency between them where there are links. This consistency is obtained through iterative single-equation estimation and solution, not through system estimation. Given the size of the model this is understandable. However, in the spirit of Keynesian econometric models, following a shock the model may not reach equilibrium in the neoclassical (CGE) sense of equality between demand and supply for each factor (although supply equals demand for each product and the value identities for each industry's inputs (products, labour, factor taxes, profits) and outputs are maintained). When the simulated tax changes are small this is unlikely to be a problem but any errors caused by the absence of market clearing equations can cumulate over time and so throw the very long-run predictions off-course from the equilibrium that prevails in CGE models. (Cambridge Econometrics argues that the world does not, in fact, operate in the manner portrayed in general equilibrium theory, and that it would be misleading to rely on projections which impose the neoclassical assumptions.)

Disaggregated models like the MDM-E3 model depend crucially on the availability and reliability of data. For this model most variables are available annually since 1971 and availability is unbalanced, e.g., the number of industry sectors is very different from the number of investment sectors. It is not easy to calculate econometric measures of how reliable the forecasts are and CE have not done it, but I suspect a large number of coefficient estimates have large standard errors. Using these coefficients to make detailed disaggregated predictions of the impact of taxes on several fuel types is not likely to give reliable results. Econometric models are good for fairly aggregate analysis when the law of large numbers might be invoked to deal with measurement errors. Their advantage is that they can summarise general dynamic trends and more specifically pick up short-run adjustment dynamics that computable models cannot do very easily. But as the degree of disaggregation increases their standard errors increase too. On the other hand, these potential disadvantages need to be traded off against the advantages of a disaggregated model in overcoming aggregation bias (for example, the failure of more aggregated models to represent properly the impact on energy demand of structural changes in the economy) and in allowing specific policies to be represented quite precisely (for example, measures that apply only to specific industries, or to specific fuels).

Of course, one might argue that the same reservations can be expressed about the reliability of the coefficients used in CGE models. However, CGE models have the advantage that they can be used to perform sensitivity analysis with the coefficients and so identify which are the important coefficients and which the unimportant, although conceivably one can also do this with econometric models. CGE models also impose the discipline of equilibrium which does not allow errors to cumulate. But they do miss out on the short run (or, in the case of capital adjustment, medium run) adjustment dynamics and on the changes in technology coefficients caused by new policy measures.

The energy and electricity sub-models of MDM make a good effort to pick up changes in technology coefficients.

In summary, econometric models offer something additional, and very often complementary, to CGE models. The assumptions in the energy and electricity sub-models of MDM seem to me to be reasonable and I suspect can pick up fairly reliably the impact of carbon taxes on energy demands. The more difficult question is whether a Keynesian-type demand mechanism across sectors is the most appropriate one to trace the impact of these taxes on the rest of the economy. There can be no straight answer to this question. With the current state of knowledge CGE models and econometric models have different things to offer; the former being better at picking up long-run equilibrium effects and the latter better at picking up the short-run adjustments and the changes in technology implicit in the time series that they use.

5. Welfare measures

Taxes have the usual distortions that welfare economics analyses under the general heading of deadweight losses. I am not addressing this issue here as there is nothing new to say about it. The new issues are whether GDP should be the only measure of welfare when choosing abatement policies or whether other issues should be brought to bear.

An abatement policy reduces carbon emissions into the atmosphere at the cost of some current and future output, measured as a percentage of GDP. Carbon emissions have long-term impacts on welfare whereas the cost of the policy is an ongoing annual flow.

1. A pure GDP measure of welfare is a calculation of the present discounted value (PDV) of the output loss versus the PDV of gain from lower emissions in perpetuity. The former is straightforward once the economic models give the output loss from the taxes. The latter is discussed at length in the Stern Review and the principles of the calculation are laid out. The choice of discount rate turns out to be critical in this evaluation because of the different timing of the gains and losses.
2. Carbon emissions, however, have other harmful effects on human welfare, which are discussed extensively in the Stern Review and in many other documents from international organisations in connection to environmental pollution, changes in animal and plant life and climate change. One cannot put a value on these in the discussion of the optimality of abatement policies, as the values are subjective. But awareness of these costs of carbon emissions can help in the design of optimal polices. The optimal taxes derived from the output cost-benefit analysis of paragraph 1 should be the minimum acceptable given the other costs of carbon emissions.
3. One may, however, argue that alternative forms of energy have their costs too, besides the output calculations. For example, wind turbines on hills and solar panels on roofs are unsightly and nuclear power carries dangers in the event of an accident. The economist is not better placed to comment about these than any other responsible citizen!