The Macroeconomic Rebound Effect and the UK Economy

Final Report to

The Department of Environment Food and Rural Affairs

by

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Contents

Report Summary

1. Introduction and background

Would a more efficient use of energy resources reduce the environmental burden of economic activity? This question has become prominent in recent years as governments across the world have implemented energy efficiency programs.

Improvements in resource productivity have been suggested as both a measure of progress towards sustainable development and as a means of achieving sustainability (Cabinet Office, 2001). The popular interpretation of resource productivity is "doing more with less": that is, of reducing the material or energy requirements of economic activity. However, the presumption of the "conventional wisdom" that underlies current policy initiatives is that improving resource productivity will lower the burdens on the environment.

In fact, there has been an extensive debate in the energy economics/ policy literature on the impact of improvements in energy efficiency in particular. This focuses on the notion of "rebound" effects, according to which the expected beneficial impacts on energy intensities are partially, or possibly even more than wholly in the case of "backfire", offset as a consequence of the economic system's responses to energy efficiency stimuli. The "Khazzoom-Brookes postulate" (Saunders, 1992) asserts that improvements in energy efficiency can actually stimulate the demand for energy, thereby nullifying the anticipated environmental benefits of such changes. Jevons (1865) was the first to argue for such an effect, in the context of improvements in the efficiency of coal use. Very recently the House of Lords have acknowledged that energy efficiency improvements alone might not deliver the expected environmental benefits.

In this report we explore the conditions under which the notion that energy efficiency is environment-enhancing would be expected to hold theoretically, and present some empirical evidence from an energy-economy-environment computable general equilibrium (CGE) model of the UK economy.

2. Theoretical analysis of resource productivity stimuli and rebound effects

We begin by providing some background that appears to underlie the "conventional wisdom" that increases in resource efficiency reduce resource use. Overall, our view is that previous studies, even those most closely associated with the view that the macroeconomic rebound effect may be substantial, tend to understate the *potential* scope for rebound and backfire effects in open economies such as the UK. However, theoretical analysis alone can only hope to identify the conditions under which such effects are likely to arise.

Undoubtedly the single most important conclusion of our theoretical analysis (in line with many previous analyses) is that the extent of rebound and backfire effects in response to energy efficiency stimuli depends on parameter values whose determination is an ***empirical*** issue. It is simply not possible to determine the degree of rebound and backfire from theoretical considerations alone, notwithstanding the claims of some contributors to the debate. In particular, theoretical analysis cannot rule out backfire. Nor, strictly, can theoretical considerations alone rule out the other limiting case, of zero rebound, that a narrow engineering approach would imply. However, in an open economy such as the UK it is virtually inconceivable that there would be no rebound effect associated with energy efficiency improvements, since this would require a whole set of extreme conditions.

Secondly, while the presence of rebound does indeed reduce the environmental gain of energy efficiency stimuli, and backfire more than offset it, relative to what would be expected from a narrow engineering perspective, this reflects the presence of an economic gain that similarly would be unanticipated by such a perspective. Finally, the theoretical analysis serves to clarify the precise nature of the evidence required to allow assessment of the likely scale of rebound effects. We use this to inform our brief summary of the existing empirical evidence.

3. Existing empirical evidence

A comprehensive review of the extant empirical evidence is well beyond the scope of this report and is, in any case, currently being undertaken by UKERC. (See Sorrell and Dimitopolous, (2005).) Rather, we attempt to provide a flavour of the evidence, and relate it to our discussion of the theoretical analysis.

While there is a significant literature relevant to the rebound debate generally, at present there seems to be a dearth of empirical evidence for the UK. There is a wide range of evidence relevant to the scale of the rebound effect available for other countries, particularly the US (e.g. Greening *et al,* 2000), much of which suggests that the rebound effect is present but is typically low-to-moderate in scale. However, these studies tend to be microeconomic in nature with a short-term focus, characteristics that may bias downwards estimates of the scale of rebound effects relevant to the macroeconomy (although our research finds greater effects in the short-run). There is, therefore, a need for UK empirical work that is focussed on the system-wide consequences of energy efficiency improvements, and that can accommodate long-run as well as short-run impacts. To address this lacuna we develop an energy-environment-economy computable general equilibrium model (CGE) of the UK. We then simulate the impact of across-the-board improvements in energy efficiency to begin to explore the likely scale of the macroeconomic rebound effect in the UK.

4. UKENVI: An energy-economy-environment CGE of the UK

CGE models are now being extensively used in studies of the energy- economy-environment nexus. The popularity of CGEs in this context reflects their multi-sectoral nature (since energy intensities vary widely), combined with their fully specified supply-side, which facilitates the analysis of both economic and environmental policies. Here we employ UKENVI, an energy-economy CGE modelling framework parameterised on UK data.

The UKENVI framework allows a high degree of flexibility in the choice of key parameter values and model closures. However, a crucial characteristic of the model is that, no matter how it is configured, we impose cost minimisation in production with multi-level production functions (see Figure 4.1), generally of a CES form but with Leontief and Cobb-Douglas being available as special cases. We generally impose a single UK labour market characterised by perfect sectoral mobility. As part of later sensitivity analysis we consider two alternative treatments of the labour market, but our central case embodies real wage bargaining.

A major objective of our research is to incorporate sustainability indicator variables into a system-wide model of the UK economy in order to track and explain the impact of policy actions (and other disturbances) on the UK's progress towards sustainable development. In the first instance, we focus on resource productivity and pollution indicators.

The main database of UKENVI is a specially constructed Social Accounting Matrix (SAM) for the UK economy. This required the construction of an input-output (IO) table for the UK for the year 2000, since an appropriate analytical IO table has not been published for the UK since 1995. A twenty-five sector SAM was then developed for the UK using the IO as a major input. The sectoral aggregation (identified in Appendix 2) is chosen to allow a focus on sectors within which there were activities affected by the EU Emissions Trading Scheme.

5. Results of the CGE simulations

Simulation strategy. The disturbance simulated using the UKENVI model is a 5 per cent improvement in the efficiency by which energy inputs are used by all production sectors. The five energy sectors in UKENVI are the coal, oil, gas and renewable and non-renewable electricity. An efficiency shock is introduced in the production of the local composite good. This shock is a one-off step change in energy efficiency, which is introduced as a composite energy-augmenting type. This introduces a beneficial supply-side disturbance, which would be expected to lower the price of energy, measured in efficiency units, generally reduce the price of outputs and stimulate economic activity.

Central case scenario. The energy efficiency improvement has a positive impact on UK economic activity, which is greater in the long run than in the short run. In the long run there is an increase of 0.17% in GDP and 0.21% in employment and exports. The expansion is lower in the short run (over which capital stocks are fixed), where a larger increase in consumption partially offsets a fall in exports**.**

The energy efficiency improvements primarily increase the competitiveness of energy intensive sectors through a reduction in their relative price. In the long run two mechanisms drive this change in competitiveness. First, the increase in energy efficiency raises the production efficiency of energy intensive sectors by the greatest amount. Second, the production techniques used in energy sectors themselves are typically energy intensive, so that the price of energy tends to fall. For both these reasons, the price of energy-intensive sectors will experience relatively large reductions in price in the long run.

A key result of this analysis is that there is a significant rebound effect. Energy consumption, measured in electricity GWh, falls from the start and reaches its long-run equilibrium reduction of 3.15% by around period 7. Thus, there is a rebound effect from the 5 per cent reduction in energy efficiency of the order of 37%, but no backfire effect is identified. The variation across energy and non-energy sectors (where activity is stimulated) can be explained by the differences in the degree to which each sector relies upon energy inputs for production, the share of value added in production and the destination of output of each sector.

Sensitivity analysis around central case scenario. Our central case results are sensitive not just to the base year values in the UK SAM, but also to: the choice of parameters for key variables in the UKENVI model; possible recycling of any additional government revenues, and the cost of any energy efficiency improvements.

Results of varying key elasticities. Since many of the key parameter values of UKENVI are not econometrically estimated, it is especially important to explore the impact of varying these on our results.

We vary the key elasticity parameters from the values used to derive the central case results. As would be expected, the higher the *elasticity of substitution between energy and non-energy intermediate inputs*, the greater GDP impact (to 0.18% as compared to the central scenario of 0.17%), and a much bigger rebound effect (60.1% compared to 37.0% in the central case). Making it easier for sectors to substitute energy for non-energy inputs will lead to bigger price reductions. Conversely, lowering the elasticity of substitution inhibits sectors from making this substitution, and so lessens the GDP gain (to 0.16%) and the extent of rebound (to 25.6%). Note that the rebound effect is really quite sensitive to the value of this substitution elasticity – more so than is the impact on economic activity.

When the *elasticity of substitution between value added and intermediate goods* is increased relative to the central scenario, the greater ease of substitution towards the now cheaper intermediate inputs produces a smaller overall effect on economic activity (0.15% stimulus to GDP as compared to 0.17% in the central scenario). Here, energy inputs are substituted in favour of labour and capital inputs, and the extent of rebound increases significantly (to 56.4% from 37.0%), despite the lower level of economic activity. Overall, our results do appear to confirm the views often expressed in the literature about the importance of the elasticity of substitution of energy for other inputs in governing the extent of the rebound effect.

As the *elasticity of export demand* is increased, sales to exports expand as a result of the greater responsiveness to the UK price reductions generated by the energy efficiency stimulus. However, the impact of varying these elasticities on economic activity is slight. This is primarily because those sectors that have the largest reduction in price are primarily the energy sectors that, in the main, do not export in the UK case. Rebound is also barely affected by changes in these elasticities.

Results of enforcing government budget constraint. In the central case and all sensitivity simulations reported so far, the improvement in energy efficiency stimulates aggregate economic output and employment. This stimulates government revenues and reduces some expenditures, but earlier results assume the government simply responds by increasing its savings. In the UKENVI model the government budget constraint can be imposed in two ways. These have quite different economic impacts.

First, additional revenue can be used to expand general government expenditure, distributed across sectors using the base-year weights. When the additional tax revenues are recycled as extra government expenditure, this acts as an exogenous demand injection and further stimulates GDP (to 0.2% from 0.17% in the central scenario – see Table 5.5). However, in this case the extent of rebound actually falls, albeit very slightly (to 36.7% from 37.0%) reflecting the relative energy intensities of government expenditures. The economic impacts are greater still if revenues are used to reduce income tax rates (with a GDP stimulus of 0.34%). Overall, the recycling of government revenues generated by the energy efficiency stimulus tends to significantly improve the economic benefits with little adverse impact (and in the case of the government expenditure stimulus a slight gain) in terms of the extent of rebound.

Results of implementing a costly energy efficiency policy. To explore the impact of costly policies we simulate the same 5% improvement in energy efficiency across all sectors, but simultaneously model a negative cost to the efficiency of labour inputs in production. This can be thought of as representing the additional costs to labour required to effect the improvement in energy efficiency. Overall, if energy efficiency improvements are costly their rebound effect will be less, but so to will the economic gain (and this could even become negative).

Results of implementing different labour market closure. In the central case scenario, and all other sensitivity so far, we have used a bargained real wage closure in the labour market in which workers' bargaining power is inversely related to the unemployment rate. Two other specifications are simulated: firstly where aggregate labour supply is exogenous, and secondly, where real wages are fixed.

Fixing aggregate labour supply in the face of energy efficiency improvements produces higher nominal and real take home consumption wages, and a small reduction in GDP in the long run (0.037%). Rebound in energy consumption falls slightly to 32.9%. A fixed real wage on the other hand, produces considerable increases in employment in the long run (up 0.95%), and an increase in GDP of 0.90%. Total energy consumption falls in the long run by 2.4%, indicating a rebound effect of 51.7%.

6. Policy implications

Rebound and backfire are of considerable potential relevance to climate change policy, since the coupling of reductions in energy use with no penalty in terms of output (the "zero-cost" ideal of the resource productivity enthusiasts) may not in fact be the win-win option suggested, due to induced effects on output and the consequent scale effect on environmental burdens. .

Our work shows that energy efficiency measures would generally be expected to generate a less than proportional fall in energy use (rebound). Our own view is that even the presence of backfire would not undermine the case for energy efficiency policy: although it does imply that environmental benefits cannot be guaranteed by such policies alone. Rebound implies that environmental improvements will not be as great as the initial percentage fall in energy use per unit output. However, the extent of rebound is ultimately an empirical issue. Our own empirical analysis suggests the likelihood of significant rebound effects in response to system-wide changes in energy efficiency (of the order of 40%) for the UK as a whole, although this does depend on the precise value of elasticities that govern the ease of substitutability of energy for other inputs. However, there is also typically an accompanying stimulus to economic activity. A clear policy implication is thus that: (i) in general, the coordination of energy policies would be beneficial and (ii) that an increased energy tax may be required to be implemented alongside the energy efficiency improvement.

Our results show some sensitivity of the rebound effect to changes in the parameter values for the elasticity of substitution between energy and non-energy intermediates; for the elasticity of demand for energy, electricity and non-energy sectors and to the costs of policies and the behaviour of the labour market. However, it is difficult to see how energy policy could in itself do much to change these parameters in the "right" direction. Indeed, improvement of information flows and reduction of transactions costs would be likely to increase effective elasticities, not reduce them.

Our sensitivity analysis reveals the importance of the treatment of the government budget, at least for the economic impact of energy efficiency improvements, if not for the scale of rebound effects. In general environmental impacts will depend crucially on precisely how the government budget is closed. For example, cutting other environmental taxes would increase overall environmental burdens, and this is also true for cuts in income tax (e.g. if consumer expenditure is more energy-intensive than government expenditure). Also, higher government spending on R&D in renewable technology, or on infrastructure for hydrogen vehicles or on low-emission trains, would reduce the *environmental* rebound associated with energy efficiency gains, driving down CO_2 emissions over time. If off-setting increases in government spending impact on environmental indicators other than those relevant to climate policy (e.g. impacts on water quality), then we need to know how substitutable gains in one environmental target area are for losses in another.

Finally, energy efficiency improvements are likely to be the result of conscious R&D investments, rather than emerging exogenously. How government behaves in terms of incentivising endogenous technological change for energy-using processes will be crucial. That government has a role in doing this comes from a recognition of the public good aspects of technological change.

It is important that, where substantial across-the-board energy efficiency improvements are being pursued, future evaluation work adopts an approach which allows the system-wide effects of efficiency improvements to be assessed. Such an approach also allows the analysis to reflect the operation of a stimulus to GDP, employment and incomes resulting directly from the increase in energy efficiency. A full Cost Benefit Analysis of efficiency effects would need to take these knock-on macro effects into account.

One important point in evaluating the macroeconomic impacts of a resource productivity change is to know whether it is a one-off shock, or a continuous process. While a one-off shock is capable of having impacts on GDP (moving it to a new equilibrium over time), only a continuous process of improvement will change the growth rate of the economy.

It is also desirable that, in the case of the use of time series or cross-section data to analyse the effects of changes in energy efficiency, that a distinction be drawn between price-induced change and technology-induced change.

1. Introduction and background

Would a more efficient use of energy resources reduce the environmental burden of economic activity? This question has become prominent in recent years as governments across the world have implemented energy efficiency programs. In the UK, the Cabinet Office (2001) set out the aims for resource productivity to reduce the impact of economic activity on the environment. The ultimate aim is to "decouple" economic activity from environmental damage. For Scotland, the First Minister stated "being more efficient with our resources will make our businesses more competitive and our economy more productive" (DEFRA, 2005, p1). The Carbon Trust (2003) also recently backed this view, reporting "as energy efficiency measures to reduce carbon emissions today are cheaper than renewable energy, Government could pursue its environmental goal at lowest cost by focusing on energy efficiency".

Internationally, the efficient use of resources has seen a growing role in policy making. The recently signed U.S. Energy Policy Act 2005 affords a central role to energy efficiency, and there are influential groups advocating the use of energy efficiency programs (such as the World Business Council for Sustainable Development and the American Council for an Energy-Efficient Economy). The "Factor 10 Club" (Schutz and Welfens, 2000, p15) argues "within one generation, nations can achieve a ten-fold efficiency increase concerning the use of energy, natural resources and other materials".

Improvements in resource productivity have been suggested as both a measure of progress towards sustainable development and as a means of achieving sustainability (Cabinet Office, 2001). The popular interpretation of resource productivity is "doing more with less": that is, of reducing the material or energy requirements of economic activity. As we note below, there are many possible interpretations of resource productivity. However, the presumption of the "conventional wisdom" that underlies current policy initiatives is that improving resource productivity will lower the burdens on the environment. In fact, there has been an extensive debate in the energy economics/ policy literature on the impact of improvements in energy efficiency in particular. This focuses on the notion of "rebound" effects, according to which the expected beneficial impacts on energy intensities are partially, or possibly even more than wholly in the case of "backfire", offset as a consequence of the economic system's responses to energy efficiency stimuli. The "Khazoom-Brookes postulate" (Saunders, 1992) asserts that improvements in energy efficiency can actually stimulate the demand for energy, thereby nullifying the anticipated environmental benefits of such changes.

There is growing discussion in the policy community of the empirical importance of the rebound effect. A very recent development is a House of Lords (2005) report that consulted on the importance of rebound for the effectiveness of UK energy efficiency policy. It notes that the way in which these impacts manifest themselves at the system-wide level are less well-known than the micro-economic effects.

> Absolute reductions in energy consumption are thus possible at the microeconomic level. However, this does not mean than an analogy can be made with macroeconomic effects. Apart from anything else, the substitution effects observable at the macroeconomic level cannot be replicated by households, where demand for a range of goods is relatively inelastic… a business on the other hand, could respond to cheaper energy by deliberately increasing consumption – using a more energy intensive process, which would allow savings to be made elsewhere, for instance in manpower (House of Lords, 2005, p29.)

These conclusions mark the first time, to our knowledge, that UK policy circles have acknowledged that energy efficiency improvements alone might not deliver the expected environmental effects. Again:

> "the 'Khazzoom-Brookes postulate', while not proven, offers at least a plausible explanation of why in recent years improvements in 'energy intensity' at the macroeconomic level have stubbornly refused to be translated into reductions in overall energy demand. The Government have so far failed to engage with this

fundamental issue, appearing to rely instead on an analogy between micro- and macroeconomic effects". (House of Lords, 2005, p102.)

In this report we build upon our earlier analysis in Hanley *et al* (2005, 2006) to explore the conditions under which the notion that energy efficiency is environment-enhancing would be expected to hold theoretically, and present some empirical evidence from an energy-economy-environment computable general equilibrium (CGE) model of the UK economy. In Section 2 we define resource productivity, summarise previous theoretical discussions and sketch our own analysis of the likely system-wide ramifications of a stimulus to energy efficiency. While we conclude, as have many others (e.g. Saunders, 2000b), that the extent of rebound and backfire is an empirical issue, the review of theory serves to clarify the key determinants of the scale of such effects and the nature of the evidence that would be required to resolve the debate. In Section 3 we provide a brief summary of existing evidence. In Section 4 we summarise the key features of our energy-economy-environment computable general equilibrium model of the UK, UKENVI. We present the results of simulating an across the board stimulus to energy efficiency in Section 5. In Section 6 we discuss the implications of rebound effects for energy policies. Section 7 is a brief conclusion. We provide a simplified summary of the structure of UKENVI in Appendix 1, discuss the construction of the model's database in Appendix 2.

2. Theoretical analysis of resource productivity stimuli and rebound effects

We begin by providing some background that appears to underlie the "conventional wisdom" that resource efficiency increases reduce resource use. We then briefly summarise previous theoretical analyses of rebound and backfire effects. Finally, we provide sketch of our own theoretical analysis of these effects. Overall, our view is that previous studies, even those most closely associated with the view that the macroeconomic rebound effect may be substantial, tend to understate the potential scope for rebound and backfire effects in open economies such as the UK. However, theoretical analysis alone can only hope to identify the conditions under which such effects are likely to arise: the issue of the scale of such effects is inherently an empirical one.

Background

As de Bruyn and Opschor (1997) have noted, the intensity with which economies utilise material and energy resources changes over time. Trends of both "dematerialisation" and "rematerialisation" have been noted by them, as by other authors (eg Young and Sachs, 1995). Perhaps based on these empirical observations, an argument has emerged in favour of deliberately improving resource productivity as a part of sustainable development policy (Weizsacker et al, 1997) and as a way of reducing the environmental impacts of economic activity (Chadwick, 1998). This academic literature has had an impact on the policy community, with increasing resource productivity being promoted by several governments and international agencies (Nordic Council of Ministers, 1999; Cabinet Office, 2001; EEA, 1999). Resource productivity measures have also emerged as official indicators of sustainability (DETR, 1999). Rather large improvements in resource productivity have been suggested as being both possible and desirable, in the case of both "factor four" and "factor ten" arguments (Weizsacker et al, 1997). For example, the UK has set targets of a 20% improvement in energy efficiency by 2010, with a further 20% improvement by 2020.

How is resource productivity defined however? Pearce (2001) suggests as the ratio of output to the resource input (Q/R), where R may be materials or energy input. Q may be interpreted as GDP, thus Q/R becomes materials or energy efficiency (output per unit of materials/ energy input). Why may these measures be of interest? The reasons lie in the motivation for society wishing to improve resource productivity, which according to Pearce (op cit) are[1]:

(a) to conserve scarce energy and materials resources
(b) to conserve the natural environments which act as the receiving 'sinks' for resources when they are converted to wastes

(c) to increase profitability in firms - provided the costs of improving resource productivity are not greater than the cost savings, profits will rise.

Pearce claims that (b) is the most important reason, since markets will in general handle both (a) and (c), whilst environmental impacts are typically non-market, and so cannot be optimally dealt with by the market, although it is important to remember that emissions are not necessarily a good proxy for environmental damage. In the UK, government has stated that (b) is the most important motivation (eg DTI, 2002). Interestingly, (c) is put forward by many authors as a reason why improving resource productivity is both good for the environment and good for industry: see Fischer-Kowalski *et al*, 1997 for evidence, and WBCSD (2000) for advocacy on this point.

Many recent analyses take the form of growth accounting exercises (eg Pearce, 2001) organised around an identity, such as that expressed in equation 1:

(1) $$R = \frac{ZP}{B}$$

Where: R is resource use; P is population; Z is output per head (Y/P) and B is resource productivity (Y/R).[2] Taking logs and totally differentiating with respect to time yields:

(2) $$\dot{r} = \dot{z} + \dot{p} - \dot{b}$$

where the lower case, dot notation denotes proportionate rates of change, so that, for example, $\dot{p} = \frac{1}{p}\frac{dp}{dt}$ (e.g. Hanley et al, 2006). This expression is taken to be a useful framework for thinking about resource productivity issues. For example, Pearce (2001) notes that to avoid increasing resource use, resource productivity growth has to be sufficient to exceed the sum of growth in per capita income and population. That is to say, $\dot{b}$ is expected to rise due to increases in resource productivity – i.e. increases in output per unit of resource use.

However, this analysis is problematic in a number of respects. First, it ignores the fact that $\dot{b}$ may rise for reasons other than increased resource productivity. For example, there may be substitution in favour of other inputs in response to alternative policy instruments such as taxes on resource use or physical controls, or other unrelated changes in input use. It also tends to equate changes in resource productivity, as defined in equation (1), with changes in resource efficiency, that is technological changes that allow greater output per unit of resource input. Therefore there is a failure to recognise that $\dot{b}$ may actually *fall* with increased resource efficiency, due to increased competitiveness in energy-intensive sectors. As the price of energy falls, in efficiency units, there may be substitution in favour of energy in local production and increased consumption demand for the outputs of energy-intensive sectors. Moreover, $\dot{y}$ and $\dot{p}$ are not exogenous variables. Any positive change in efficiency will increase competitiveness and therefore, potentially, output per head and, in general, population. However, while induced changes in the latter prove important for analyses of regional economies (Hanley *et al*, 2005), we assume that they are at most of second order importance for the UK as a whole, and we abstract from them in what follows.

Thus, while discussions based around equation (2) (or one of its variants) are not without interest, it is important to note that these are incapable of adequately identifying the implications of an increase in resource productivity. For this we require a theory of the system-wide links between resource productivity stimuli and output. We begin with a brief summary of past analyses of rebound and backfire effects.

Past theoretical analyses of macroeconomic rebound effects

It is instructive to provide a brief account of the literature on what has come to be known as the macroeconomic rebound effect, which focuses on the Khazoom-Brookes postulate. The literature is couched in terms of energy efficiency, but the principles apply to other forms of resource productivity. In fact, both Khazoom (1980) and Brookes (1990) acknowledge their intellectual indebtedness to Jevons (1865) as being the originator of the basic idea that energy efficiency improvements could lead to an increase in energy demand. Jevons (1865), concentrated on the possible exhaustion of a finite natural resource, namely coal. While Jevons' (1865) analysis focuses on a single energy source, there can be little doubt of the system-wide importance of coal in fuelling the industrial revolution, and so changes in the efficiency of its use undoubtedly had macroeconomic effects. While largely an empirical study, in a key passage, examining the argument that a more efficient use of coal would prolong its life, Jevons (1865, p140) argues, "it is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth." Clearly Jevons (1865) rejected the argument that a more efficient use of coal would necessarily reduce the demand for coal. He argued (1865, p141) "it is the very economy of its use which leads to its extensive consumption. It has been so in the past, and it will be so in the future". Indeed, Jevons (1865, p141-142) is clear on the causes of this counter-intuitive result.

> The number of tons used in any branch of industry is the product of the number of separate works, and the average number of tons consumed in each. Now, if the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price pig-iron will fall, but the demand for it increase; and eventually the greater number of furnaces will more than make up for the diminished consumption of each.

The modern "conventional wisdom" on efficiency seems to have neglected Jevons' insight from over one hundred years ago. The same arguments, namely that increased efficiency can reduce our dependence on oil (as criticised by Brookes, 1978) or limit environmental impacts (Pearce, 2001) are being made once again. However, the resurgence of these arguments has been questioned in the economic and environmental literature. This critical work supports the ideas of Jevons with modern economic tools of analysis. Wilhite and Norgard (2004, p992) for instance, argue "the policy and the research at the centre of the discourse on energy sustainability suffer from a self-deception, which resolves around the equation of 'efficiency' with 'reduction'".

While Jevons (1865) effectively argues for backfire as Alcott (2005) notes, our own view is that there is fact nothing inevitable about backfire (though we do believe that zero rebound is virtually inconceivable). Modern theory has helped to identify the conditions that are likely to facilitate significant rebound and even backfire. Saunders' (1992, 2000a,b) analyses of rebound and backfire effects provide probably the best known, and most formal, analyses of the issues from an explicitly macroeconomic perspective. Khazzoom's (1980) work is partial equilibrium in nature, taking aggregate incomes and output as given. Brookes (1990) began the development of the argument in a macroeconomic context, and Saunders' analyses extend this. (The subsequent interchange between Grubb (1990, 1992) and Brookes (1992,1993) centred mainly on the likely scale of rebound effects so we consider it briefly in our discussion of empirical evidence, but see also below.) Saunders' (1992,2000a,b) analyses the impact of energy efficiency changes using a model of neoclassical growth, and these contributions have come to be widely regarded as offering the strongest theoretical support for macroeconomic rebound and backfire effects. While Howarth's (1997) challenge to Saunders' (1992) support for the likelihood of significant rebound and backfire effects, namely that Saunders had failed to distinguish between energy and the services of energy, is regarded as convincing by some (e.g. Herring, 1999), it appears to us to have been effectively countered in Saunders (2000a), where it is shown that Howarth's assumption of a Leontief production function for the production of energy services is crucial to his challenge.

While our own view is that Saunders (1992, 2000a,b) adds significantly to our understanding of the long-run macroeconomic impacts of energy efficiency changes, we also believe that the context in which he chooses to analyse their impact is rather restrictive and, despite being regarded as one its leading advocates, inadvertently tends to understate the case for macroeconomic rebound and backfire effects. In particular, it leads to an over-emphasis of the significance of the elasticity of substitution of energy (or energy services) for other inputs in governing the extent of rebound or backfire, an emphasis reflected in other contributions (e.g. Howarth, 1997). This elasticity is indeed important, and it is true that the greater its value, other things being equal, the greater is the likely the extent of rebound. However, even if it is zero, rebound and even backfire may still occur. We next turn to sketch our preferred theoretical analysis.

System-wide impacts of an increase in resource productivity

We examine the system-wide impact of improved resource productivity within a general equilibrium framework. Here we focus on enhanced *energy* efficiency, but the general approach can be extended to other resources. The problem is tackled by imposing energy-augmenting technical progress within the aggregate production structure. This has the effect of increasing energy efficiency but actually reduces the price of energy, measured in efficiency units:

[3] $$\varepsilon = (1+\rho)E$$

where ε is an efficiency unit of energy, E is one physical unit of energy and ρ is the change in energy efficiency. Then the price of an efficiency unit of energy is given by

[4] $$p_{\varepsilon} = \frac{p_E}{1+\rho}$$

The overall impact of a change in energy efficiency on the use of energy depends solely on the general equilibrium own-price elasticity of demand for energy. Where this is greater than unity, the fall in the implicit price of energy will generate an increase in expenditure on energy so that overall energy use would rise: substitution and output effects would dominate efficiency effects.

The simplicity of this result, and its significance, appear not to have been fully appreciated in the wider literature, although many analyses come close. This seems in part to be tied to the fact that the debate in the literature centres around concepts of "rebound" and "backfire". Saunders (e.g. 2000a) defines rebound as R, equal to unity plus the elasticity of physical energy use ($1+\eta_E$) with respect to the efficiency augmentation factor ($1+\rho$). In fact, it is straightforward to show that R is simply the (absolute value of the) elasticity of the demand for energy in efficiency units (η_ε) with respect to ($1+\rho$). That is to say: $R \equiv \eta_\varepsilon = 1+\eta_E$. In turn η_ε is simply the (absolute value of the) price elasticity of the demand for energy in efficiency units ($0 \leq \eta_\varepsilon \leq \infty$). In the present context rebound is said to occur if the demand for energy falls less than proportionally to the stimulus to energy efficiency. Thus zero rebound (R=0) would require the demand for efficiency units of energy to be unaffected by the efficiency stimulus, so that the demand for physical units of energy would decline equi-proportionately ($\eta_E = -1$). This is precisely the result that occurs if $\eta_\varepsilon = 0$. Rebound is said to be unity (R=1) if the demand for efficiency units of energy increases by the same percentage as the effective price of energy falls, so that the physical quantity of energy used remains unchanged ($\eta_E = 0$). This result is associated with a unitary price elasticity of the demand for energy in efficiency units ($\eta_\varepsilon = 1$). Finally, "backfire" arises (R>1) wherever the quantity of energy demanded actually increases relative to its initial level in response to an energy efficiency stimulus ($\eta_E > 0$), a result that is assured by a price elasticity of energy demand that is greater than unity, so that the demand for efficiency units of energy increases more than in proportion to the fall in the effective price of these units. "Rebound" is nothing more than the (absolute value of the) price elasticity of demand for energy in efficiency units.

Expressed in this way, it is comparatively straightforward to clarify a number of issues. Assume, for now, a small open economy that produces a single output by combing two inputs, "value-added" (in turn produced by capital and labour) and an intermediate energy composite. This is, in fact, very similar to the macroeconomic production function that forms the basis of Saunders' (2000a) analysis of rebound and backfire effects, except that Saunders effectively adopts a closed-economy neoclassical growth model. In fact, it is fairly straightforward to capture openness with a slight modification to the demand side to recognise the price-elasticity of demand of the single ouput in this context. This would allow derivation of the macroeconomic, or system-wide, demand for energy as a "derived demand" for a factor of production in an open-economy context. The demand for energy (and labour and capital) in this system "derives" solely from the demand for the country's output (since we assume for simplicity that energy is consumed only as an intermediate good). In these circumstances, we can invoke Hicks's (1963) laws of derived demand to identify the determinants of the price elasticity of demand for energy – and therefore the scale of rebound effects in this simple economy – given that we have established that rebound is nothing other that the absolute value of the price elasticity of demand in efficiency units.

First, Saunders' (2000) analysis argues that rebound and backfire are "apparently" more likely the greater is the elasticity of substitution of energy for other inputs (labour, capital). In fact this is one of Hicks' "Rules of Derived Demand", so the result is general in the sense that it is not dependent on the specific production functions considered by Saunders. As energy efficiency increases, and the price of an efficiency unit of energy falls, the greater the ease with which energy can be substituted for other factors, the greater the stimulus to energy demand. However, the conclusion that there is consequently a "key policy tradeoff", so that if this elasticity of substitution is low "one worries less about rebound and should incline toward programs aimed at creating new fuel-efficient technologies" (p446) is strictly incorrect. The problem here is that rebound, or the price elasticity of demand for electricity in efficiency units, does not depend *only* on the elasticity of substitution of energy for other inputs. Indeed, even if this elasticity is precisely zero, as under Leontief technology, rebound and indeed backfire remain perfectly feasible, if less likely. There appears to be a widespread, but mistaken, belief in the literature that low elasticities of substitution between energy and other inputs (indeed it is often asserted that this is the case for elasticities less than unity) imply that rebound must be small and backfire impossible.

A second, and key, factor omitted by neglecting openness and the potential importance of the demand side of the product market is that rebound is increasing in the price elasticity of the demand for the output into which energy is an input. This is potentially a critical determinant of the extent of rebound or backfire, yet its significance is perhaps not as widely recognised as it deserves to be in the literature. It is, of course, occasionally mentioned but typically in a microeconomic context, and often to be dismissed on empirical grounds (Greening *et al*, 2000). It is true that the significance of this factor is moderated by a third: energy's share in the relevant scale variable (e.g. GDP in a KLE value-added production function), which is typically of modest scale. For the subject economy, however, openness to trade may imply a highly price-elastic demand for the output produced by the economy. This implies that the derived demand for energy within the subject economy may also be price-elastic. In these circumstances an economy-specific stimulus to energy efficiency reduces the price of an efficiency unit of energy and the good produced, so stimulating the demand for output, resulting in significant rebound and perhaps backfire.

Finally, the price elasticity of demand for energy will be greater the greater the elasticity of supplies of other factors. These elasticities are almost certain to increase with the duration of the time interval under consideration. Labour supplies could be increased, for example, by working longer hours, greater participation rates or, in a regional and even national context, through in-migration. Capital stocks can be augmented gradually through investment. However, such processes are likely to be extended, and so time may be a very important factor in governing the scale of rebound. This has, of course, been recognised in the literature, though not expressed in quite this way. These points all have echoes in the literature, but in the present context they follow very straightforwardly and unambiguously.

Furthermore, some aspects of the debate on rebound and backfire seem curious in the current context. Thus the idea that rebound is an unlikely phenomenon, a view propounded by some green critics and by some engineers seems virtually inexplicable. The restrictiveness of the zero rebound (elasticity) case is immediately apparent from our more general macroeconomic analysis. For R=0, it would certainly not be sufficient for energy to be combined with other inputs through Leontief technology (zero elasticity of substitution), as some of the literature appears to suppose. The requirement that the demand for energy be entirely invariant with respect to own price also requires that relevant goods' demands (including international demands) be completely unresponsive to price changes, or energy's share in the relevant composite be approximately zero. We have difficulty imagining any real-world example, especially in the context of a small open economy. Equally, it is clear that any notion that backfire can be ruled out on the basis of theoretical arguments is groundless. This is an empirical issue, dependent on the price elasticity of the system-wide demand for energy being greater than unity in the specific context.

As with any simple theoretical analysis a number of qualifications/ extensions are appropriate, but none undermine the essential message that we should find neither rebound nor backfire surprising. First, energy is, of course, demanded as a final good and households demand it directly too for heating and lighting (as well as indirectly via the energy content of consumption goods). This simply creates other possibilities of substitution and income effects, which have been recognised by a number of contributors to the debate (e.g. Greening *et al*, 2000) to match the output and substitution effects apparent on the supply side. These effects will tend to provide reinforcing arguments for rebound and backfire, as consumers substitute towards energy intensive goods in the face of an efficiency-induced fall in the relative price of energy, and real incomes rise, further stimulating the demand for normal goods (and therefore probably energy, both directly and indirectly). Saturation effects could certainly limit any tendency for the demand for energy to increase as a consequence of incorporating households' behaviour directly, and it almost certainly is the case, as implied by the earlier quotation from the House of Lords (2005), that substitution possibilities may be more limited for households. Secondly, some argue that the response to energy price rises and falls is likely to be asymmetric (and there appears to be supporting evidence – see below), reflecting, for example, adoption of new technologies not easily reversible in response to energy price hikes. The argument here would be that the scope for rebound and backfire in response to efficiency improvements should focus on the elasticity with respect to price falls, which would be lower than that with respect to price rises.

Reference has also sometimes been made to the possible "transformational" effects of energy efficiency increases (e.g. Greening *et al*, 2000), by which we presume is meant either that technical change itself and/or household utility functions are themselves endogenous in the very long-run. While such effects could reinforce rebound effects and can, in principle, be incorporated into the analysis, the empirical evidence is, to our knowledge, extremely limited to date, so that calibration would be problematic, and we follow Greening *et al* (2000) in not pursuing it further here.

Of course, in practice there is not one good but many, with wide variation in energy intensities of production and substitution and demand elasticities, introducing a wide diversity of relative price changes in response to energy efficiency stimuli. Furthermore, there are a range of energy inputs, with substitution possible among them. These observations in themselves appear to militate against the use of aggregate studies given that these must be the outcome of the reactions of numerous transactors. In these circumstances "the" system-wide price elasticity of demand for energy is in fact a complex combination of a large number of structural (e.g input intensities) and behavioural (e.g. substitution) parameters, which in practice defy a solely analytical approach. This provides a part of the motivation for the CGE modelling approach that we pursue here.

There is a significant and growing literature that focuses on barriers to the adoption of the most efficient energy technologies (e.g. Sorrell *et al*, 2004). And Grubb's (1990, 1992) interchanges with Brookes (1990, 1992, 1993) reflect this perspective. Conventional neoclassical behavioural functions of the type assumed here, it is argued, fail to capture some of the significant barriers to penetration of new technologies, including, for example, imperfect information, the presence of some significant transactions costs that are neglected in the optimisation processes that underlies the functions. While we there is clear microeconomic evidence that such considerations matter in practice, they cannot be properly captured by macroeconomic approaches, except imperfectly to the extent that they impact on the values of the key parameters. Ultimately these contributions simply reinforce the main conclusion that rebound is an empirical issue, though they do suggest reasons why rebound and backfire may be rather less significant empirically than they otherwise would be.

Undoubtedly the single most important conclusion of our analysis so far is that the extent of rebound and backfire effects in response to energy efficiency stimuli is always and everywhere an ***empirical*** issue. It is simply not possible to determine the degree of rebound and backfire from theoretical considerations alone, notwithstanding the claims of some contributors to the debate. In particular, theoretical analysis cannot rule out backfire. Nor, strictly, can theoretical considerations alone rule out the other limiting case, of zero rebound, that a narrow engineering approach would imply. However, in an open economy such as the UK it is virtually inconceivable that there would be no rebound effect associated with energy efficiency improvements, since this would require zero sensitivity to relative price changes throughout the entire system (not just Leontief production technology). Even if it is conceded that neoclassical economic theory tends to exaggerate the flexibility of the economic system by abstracting from some real-world frictions, the zero rebound case seems extremely unlikely to be of any empirical relevance. The restrictiveness of the conditions required for zero rebound does not, however, appear to be widely appreciated.

Secondly, while the presence of rebound does indeed reduce the environmental gain of energy efficiency stimuli, and backfire more than offset it, relative to what would be expected from a narrow engineering perspective, this reflects the presence of an economic gain that similarly would be unanticipated by such a perspective. Whatever the judgment on Jevons' (1865) overall analysis, his insight that dramatic improvements in the efficiency in the use of coal were a key driver of the industrial revolution is worthy of serious consideration. This does not, of course, imply that the environmental effects of rebound are unimportant, but the presence of economic gains does suggest the possibility, at least in principle, of devising a policy package that may yield a "double dividend".

Finally, the theoretical analysis serves to clarify the precise nature of the evidence required to allow assessment of the likely scale of rebound effects. We use this to inform our brief summary of the existing empirical evidence, which follows.

3. Existing empirical evidence

A comprehensive review of the extant empirical evidence is well beyond the scope of this report and is, in any case, currently being undertaken by UKERC. (See Sorrell and Dimitopolous, (2005), who do note, however, that the quantity, heterogeneity and complex nature of much of the evidence is likely to render a full Evidence Based Policy and Practice approach impractical.) Rather, we attempt to provide a flavour of the evidence, and relate it to our discussion of the theoretical analysis. A natural starting point is to consider available evidence on the price-elasticity of the derived demand for energy by firms, given its likely central importance overall.

Some evidence focuses on trends in energy intensities both at the micro (household and industry) and the macroeconomic levels (energy intensities of GDP). While these studies provide much useful background information (e.g. Herring, 1999; Schipper and Grubb, 2000, who judge that there is little evidence of significant rebound effects in IEA countries), they cannot strictly, in themselves, be used to resolve the extent of rebound, because of the difficulties of interpreting such ratios alluded to in our discussion of growth accounting approaches. (The decompositional approach explored by Schipper and Grubb (2000) is amenable to generalisation using input-output (IO) attribution methods and appropriate IO tables and social accounting matrices.) There are so many influences on these ratios that are nothing to do with energy efficiency *per se*, that it is not possible to come to any firm conclusions about the likely extent of rebound. Of course, Jevons' own (1865) analysis is based on a particular causal interpretation of changing coal efficiencies and industrial output, and equally cannot be regarded as establishing the importance of "backfire" during the industrial revolution. In fact, however, Schipper and Grubb (2000, p386) appear to accept the importance of significant macroeconomic rebound effects in this case and in others "when energy availability, energy efficiency, and energy costs are a significant constraint to activity and therefore energy use!", a view that echoes Grubb's (1990, 1992) earlier contributions. Their view is that typically in high-income, developed economies saturation effects are likely to be important in governing household demands (though low income households are an exception), and energy costs are not a sufficiently important element in total costs to lead to an expectation of significant rebound effects. While moderate energy shares in output together with saturation effects (and asymmetrical responses to energy prices) do indeed imply that rebound would be lower than it otherwise would be, this is not sufficient to establish that such effects are insignificant. Furthermore, at least in principle, economic modelling approaches allow us to isolate the impact of energy efficiency changes on the economy and the environment by seeking to ensure that the *ceteris paribus* condition is met, so that all other influences on energy use indicators are controlled for. So for example, Hogan and Jorgenson (1991) found that energy intensity increased during the 1990s once the response to the 1970s oil price hikes were allowed for.

There is evidence on the elasticity of substitution of energy for various other inputs, drawn mainly from applied econometric studies of production or cost functions. As Howarth (1997) notes there was quite a lot of research into this issue in the 1970s and early 1980s (Berndt and Wood, 1979). There seemed to be evidence of capital-energy complementarity from time series studies, but substitutability from cross-section studies, which Solow (1987) argued reflected problems in the aggregate production function approach. Howarth (1997) also refers to other research which concludes that there is an elasticity of substitution between energy and non-energy inputs that is less than unity, but this does not, for reasons given in the preceding section of the report, validate his conclusion (on p2) that "the degree of substitution required for energy efficiency improvements to support increased energy uses is unlikely to arise in real-world economic systems..". This included a reference to the work of Manne and Richels (1992) who estimated an elasticity of substitution of 0.4 between energy and value-added. Greening *et al* 's (2000) extensive survey of US work reports some studies that have found an elasticity of substitution greater than one (Chang, 1994; Hazilla and Kop, 1986), but the vast majority of estimates are less than unity, and they conclude that the size of the rebound from substitution is "small to moderate".

Bentzen (2004) considers the direct rebound effect of improvements in energy efficiency for U.S. manufacturing using a dynamic ordinary least squares approach. Aggregate time series data are used to generate translog production function, from which factor demand equations are derived. A significant rebound effect of 24 per cent for the U.S. manufacturing sector's energy use is reported. It is argued that this may be an upper bound as aggregate data are used, and that structural change will have an impact on energy consumption. Laitner (2000), on the other hand, tests for evidence of the direct rebound effect in the U.S. and finds that the macroeconomic impact is small. His results are derived from assuming a simplified relationship between carbon emissions and a combination of GDP, energy prices and technology policy. As such, this work takes a reference scenario for the change in these variables between 1998 and 2010 and compares this counterfactual to other scenarios where technology policy (such as an improvement in energy efficiency) is activated.

Greening *et al*'s (2000) review recognises the potential impact of energy efficiency improvements coming through improved competitiveness (the output effect), but "although there is some rebound effect resulting from increases in industry output, the magnitude appears to be small". However, this conclusion is based on a deduction of the likely scale of effects, given an assumption of a unitary elasticity of market demand for output. In an open economy price elasticities of demand could be substantially in excess of unity (and in the limiting, "law of one price", case approximate infinity). On the other hand, Berkhout *et al* (2000) also recognise the importance of price elasticity of demand, and report the results of research which suggests price elasticities of demand (mainly for the Netherlands) for various energy sources as significantly below unity, so that rebound ranges from 0 to 30%.

Evidence on household demands is also reviewed by Greening *et al* (2000), and they again find evidence of only moderate rebound effects, though again mainly from microeconomic studies with a comparatively short-term focus. Brännlund *et al* (2004), on the other hand, use data from the household consumption baskets of Swedish consumers to track how these have changed over time, and finds a backfire effect - so that the rebound effect in consumption is sufficient to *more than* offset the initial efficiency improvement, such that consumption actually increases – with a 20 per cent increase in energy efficiency increasing total CO_2 emissions by 5 per cent. Roy (2000) uses case studies of households and industries in India to estimate price and income elasticities for energy services. His results show that for households there is evidence of a clear rebound effect of the order of 50 per cent, with all the improvement in energy efficiency negated when the real income effects of cheaper energy are considered.

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Zein-Elabdin (1997) examines the direct and secondary fuel use effect in estimating the size of the rebound effect that could arise from the use of more efficient wood-burning stoves in the Sudan. He estimates supply and demand equations for charcoal in Khartoum over the period 1960 to 1990. He notes that measuring the change in fuel consumption by multiplying the change in fuel efficiency by the number of stoves in use merely produces an estimate of the first-round effects. As Zein-Elabdin (1997, p471) writes, "by definition, improved stoves are designed to precipitate changes in household behaviour in relation to energy use; therefore, their long-term impact depends on these higher-order effects, which, if sufficiently large, could undermine this strategy".

The rebound effect in Zein-Elabdin (1997) is estimated as

$$dC_T = (\delta s + \alpha \log \phi) dC$$

where dC is the fuel efficiency improvement from new stoves, δ is the income elasticity, s is the share of charcoal in the household budget, α is the price elasticity of demand, and ϕ is the supply elasticity. His results estimate that 42 per cent of the expected fuel efficiency gains from improved stoves may be lost to purchases of fuel, thus "a stove designed to cut fuelwood consumption by 30% will in reality achieve a reduction of 17.49% (Zein-Elabdin, 1997, p472). His recommendations for the distribution of more efficient stoves are that, on the demand-side, they are focused more towards areas where there is low demand elasticity, or, on the supply-side, policies are enacted to raise the elasticity of supply.

Where the policies are designed to have impacts that are felt across all industrial sectors of the economy, such as efficiency-improving policies, a system-wide, macroeconomic or general equilibrium approach is appropriate and necessary. In their survey of the rebound effect Greening *et al* (2000) found one paper that examined the economy-wide effects of improved efficiency (Kydes, 1997). Greening *et al* (2000, p397) note, “prices in an economy will undergo numerous, and complex adjustments. Only a general equilibrium analysis can predict the ultimate impact of these changes”. Computable general equilibrium (CGE) models could thus provide a vehicle for the estimation of macroeconomic impact of energy efficiency policies, and provide the analysis that the House of Lords (2005) seeks. A small number of CGE papers were published on this subject in the 1990s, e.g.; Dufournaud *et al*, 1994; Semboja, 1994; Kydes, 1997. However, since Greening *et al*’s (2000) review, there has been an expanding literature using CGE models to examine the system wide impacts of improvements in efficiency, e.g. Grepperud and Rasmussen, (2004); Glomsrød and Taoyuan, (2005); and our own previous analyses reported in Hanley *et al*, (2005, 2006).

In Dufournaud *et al* (1994), the specific policy under consideration is the introduction of more efficient wood burning stoves, while for Glomsrød and Taoyuan (2005) the policy is the development of coal cleaning facilities, providing a higher energy content coal product. In the case of Hanley *et al* (2005), the change is improved resource (energy) productivity across all sectors of the economy. In each case, the intention of the study is to examine the system-wide consequences of the improvements in efficiency at the microeconomic level. The CGE analyses have typically found that the rebound effect cannot be ignored, and indeed, have argued that it should be considered when policy aimed at improving energy efficiency is formulated.

In their conclusion, Glomsrød and Taoyuan (2005, p533) note “the attractive energy efficiency gains stimulates energy use to an extent that dominates over the initial energy saving. This rebound effect is significant and not modified through the labour market, as the increasing economic activity made possible by better use of energy does not make real wages go up. The improved energy efficiency allows for a significant expansion of production capacity, and the economy becomes more energy intensive”. To combat this effect, they suggest a joint implementation of other measures to complement the energy efficiency improvements, in order that there would be no bias towards higher energy intensive sectors. Hanley *et al* (2005, 2006) also examine energy efficiency using a CGE model. Like Glomsrød and Taoyuan (2005), their results of rebound and backfire can be tracked to the impact of changes in the real price of energy, brought about by increases in energy efficiency (raising the level of economic output which can be produced for a given level of energy inputs). Hanley *et al* (2005, 2006) find evidence of backfire, but emphasise the likely importance to this result of: the importance of electricity exports in the subject economy (Scotland), the regional context of the analysis, in particular the impact in-migration has in reinforcing rebound effects, and the assumption of a regional-specific (rather than UK-wide) energy efficiency stimulus. The contrast between the results reported in Hanley et al (2005, 2006) for Scotland and those reported here for the UK (for a model with a virtually identical set-up), serve to emphasise the importance of the structure of the economy and the values of key parameters (including demand and substitution elasticities) in governing the extent of rebound, a point reinforced by our sensitivity analysis below.

While there is a significant literature relevant to the rebound debate generally, at present, there seems to be a dearth of empirical evidence for the UK. For instance, DTI (2002) notes that "there is little empirical evidence at the sectoral or economy-wide level" of improving resource productivity, and that "it is difficult to forecast changes in the environment" as a result of encouraging improvements in resource productivity. There is, as we have seen, a wide range of evidence relevant to the scale of the rebound effect available for other countries, particularly the US (e.g. Greening *et al,* 2000), much of which suggests that the rebound effect is present, but is typically low-to-moderate in scale. However, these studies tend to be microeconomic in nature with a short-term focus, characteristics that may be likely to bias downwards estimates of the scale of rebound effects relevant to the macroeconomy. There is, therefore, a need for UK-oriented empirical work that is focussed on the system-wide consequences of energy efficiency improvements. We next outline the structure of the UK CGE model that we develop to allow us to begin to explore the likely scale of the macroeconomic rebound effect in the UK.

4. UKENVI: An energy-economy-environment CGE of the UK

CGE models are now being extensively used in studies of the energy-economy-environment nexus at the national (e.g. Beausejour *et al* (1995), Bergman (1990), Conrad and Schroder (1993), Goulder (1998) and Lee and Roland-Holst (1997), and Conrad (1999) provides a review) and regional levels (e.g. Despotakis and Fisher (1988) and Li and Rose (1995)). The popularity of CGEs in this context reflects their multi-sectoral nature combined with their fully specified supply-side, facilitating the analysis of both economic and environmental policies. Here we employ UKENVI, a CGE modelling framework parameterised on UK data.[3] We next provide a brief description of the general model framework. A more formal description is given in Appendix 1.

General structure

UKENVI has 3 transactor groups, namely households, corporations, and government; 25 commodities and activities, 5 of which are energy commodities/supply (see Figure 1 and Appendix 2 for details); and two exogenous external transactors (RUK and ROW). Throughout this paper commodity markets are taken to be competitive. We do not explicitly model financial flows.

The UKENVI framework allows a high degree of flexibility in the choice of key parameter values and model closures. However, a crucial characteristic of the model is that, no matter how it is configured, we impose cost minimisation in production with multi-level production functions (see Figure 1), generally of a CES form but with Leontief and Cobb-Douglas being available as special cases. There are four major components of final demand: consumption, investment, government expenditure and exports. Of these, real government expenditure is taken to be exogenous. Consumption is a linear homogeneous function of real disposable income. Exports (and imports) are generally determined via an Armington link (Armington, 1969) and are therefore relative-price sensitive. Investment is a little more complex as we discuss below.

We generally impose a single UK labour market characterised by perfect sectoral mobility. We consider three alternative treatments of the labour market. First, we include an exogenous labour supply closure, which, in effect, implies a completely wage-inelastic aggregate labour supply function. This is quite a common labour market closure in national CGE models, but is clearly a limiting case according to which the real wage adjusts continuously to ensure equality of aggregate labour demand and the fixed aggregate labour supply. Nonetheless it is a useful benchmark. As an alternative limiting case, we incorporate a real wage resistance closure, in which the real consumption wage is fixed and total employment changes to ensure labour market equilibrium. In effect labour supply is infinitely elastic (over the relevant range) at the prevailing real wage. The final case that we consider is where wages are subject to a bargained real wage function (BRW) in which the real consumption wage is directly related to workers bargaining power, and therefore inversely to the unemployment rate (e.g. Minford *et al*, 1994). This hypothesis has received considerable support in the recent past from a number of authors. Here, however, we take the bargaining function from the econometric work reported by Layard *et al* (1991):

$$[4] \qquad w_{s,t} = \alpha - 0.068u_s + 0.40w_{s,t-1}$$

where: w and u are the natural logarithms of the UK real consumption wage and the unemployment rate respectively, t is the time subscript and α is a calibrated parameter.[4] Empirical support for this "wage curve" specification is now widespread (Blanchflower and Oswald, 1994), and it is our preferred labour market closure.

Within each period of the multi-period simulations using UKENVI, both the total capital stock and its sectoral composition are fixed, and commodity markets clear continuously. Each sector's capital stock is updated between periods via a simple capital stock adjustment procedure, according to which investment equals depreciation plus some fraction of the gap between the desired and actual capital stock. This process of capital accumulation is compatible with a simple theory of optimal firm behaviour given the assumption of quadratic adjustment costs. Desired capital stocks are determined on cost-minimisation criteria and actual stocks reflect last period's stocks, adjusted for depreciation and gross investment. The economy is assumed initially to be in long-run equilibrium, where desired and actual capital stocks are equal.[5]

Treatment of energy inputs to production in UKENVI

Figure 4.1 summarises the production structure of UKENVI. This separation of different types of energy and non-energy inputs in the intermediates block is in line with the general 'KLEM' (capital-labour-energy-materials) approach that is most commonly adopted in the energy/environmental CGE literature. There is currently no concensus on precisely where in the production structure energy should be introduced, for example, within the primary inputs nest, most commonly combining with capital (e.g. Bergman 1988, 1990), or within the intermediates nest, which is the approach we adopt here (e.g. Beauséjour *et al*, 1995).

The multi-level production functions in Figure 1 are generally of constant elasticity of substitution (CES) form, so there is input substitution in response to relative price changes, but with Leontief and Cobb-Douglas (CD) available as special cases. In the application reported in Section 5 below, Leontief functions are specified at two levels of the hierarchy in each sector – the production of the non-oil composite and the non-energy composite – because of the presence of zeros in the base year data on some inputs within these composites. CES functions are specified at all other levels.

In view of the importance of the size of the relevant elasticities in our theoretical analysis of the rebound effects, and the wide variation in the estimated values of these key parameters noted in our discussion of existing evidence, we consider it essential to conduct sensitivity analysis of our results.

Modelling pollution generation in UKENVI

The simplest way to model pollution as a result of economic activity is through fixed coefficients linking pollution outputs to each sector's output level. This approach was one of the earliest steps in general equilibrium economy-environment modelling, developed in Leontief's (1970) environmental I-O framework. Nonetheless, it remains common in both I-O and more general CGE modelling e.g. Ferguson *et al* (2005). However, the major limitation of relating emissions to sectoral outputs only is that there is no scope for changes in emissions due to technical substitution *within* sectors. That is to say, if pollution coefficients are output-based and/or only pure Leontief technology is modelled, then the only way to reduce emissions within any sector is to reduce that sector's output. In discussing this issue, Beghin *et al* (1995) identify three underlying components of changes in emissions levels over time. The first component is c*omposition:* the change in pollution induced by a change in the commodity composition of aggregate production (more or less dirty/clean goods). Secondly, t*echnology* relates to evolving cleaner technologies (which usually result in a change in the input mix). Finally, s*cale:* the increase/decrease in pollution attributable to an increase in aggregate economic activity.

Where modelling of pollution involves simply relating emissions of pollution to sectoral outputs, only the composition and scale effects will be captured. The easiest way of modelling the technology effect will involve linking pollution emissions to production techniques through input-based pollution coefficients. It is useful to further split Beghin *et al*'s (1995) 'Technology' effect into two parts:

(a) *Cleaner Technology* – evolving cleaner technologies independent of the input mix (e.g. installing catalytic converters in cars – this would mean a change in the emissions factor applied to the combustion of petrol in cars).

(b) *Input substitution* - changing the input mix towards cleaner types of energy/fuel (e.g. changing from regular to low sulphur diesel) or towards non-energy inputs (e.g. reducing the amount of energy used per unit of existing capital).

Of course, there may be instances where both (a) and (b) would occur together – for example, in switching from oil to gas powered heating systems. However, it is useful to make the distinction because the manner in which (a) and (b) are captured in a CGE modelling framework differs. Input substitution, i.e. factor (b), will be captured endogenously in a production structure with fixed input-pollution coefficients and appropriate possibilities for input substitutions. Such input substitutions would typically occur in response to a change in relative prices. However changes in technology (i.e. case (a) above) are likely to involve adjustment of relevant input-pollution coefficients and/or changes to the production structure to reflect differing technical relationships in sectors and/or particular input mixes where adjustments have occurred.

The present model captures input substitution by relating emissions of CO_2 to the different types of energy use at different levels of the local energy nest in Figure 1. CO_2 emissions from the use of imported energy inputs are captured through the use of fixed import pollution coefficients at the higher nests where the RUK and ROW composite commodities are determined.[6] The input- and import-pollution coefficients are determined using data on the CO_2 emissions intensity of different types of fuel use in the UK economy. The application of fuel-use emissions factor data is fairly straightforward in the case of CO_2 emissions, as these are primarily dependent on fuel properties rather than combustion conditions and/or technology. In the environmental CGE literature, models that adopt an input-pollution approach have indeed tended to focus solely or primarily on CO_2 emissions (see Turner, 2002, for a review).

However, modelling input-pollution relationships becomes more complex when it comes to non-CO_2 emissions. This is because non-CO_2 emissions tend to be dependent not only on fuel type, but also combustion conditions and technology, meaning that appropriate emissions factors are likely to be more difficult to identify and numerous for models with a high level of sectoral detail. Thus, at this time we do not attempt to extend the input-pollution approach to the other five pollutants modelled here (sulphur dioxide, methane, nitrous oxide, carbon monoxide and PM10). Instead, we continue to adopt the basic output-pollution method in the case of these pollutants (see equation 22 in Appendix 1).

Sustainability indicators in UKENVI

A major objective of our research is to incorporate sustainability indicator variables into a system-wide model of the UK economy in order to track and explain the impact of policy actions (and other disturbances) on the UK's progress towards sustainable development. In the first instance, we focus on resource productivity and pollution indicators.

The main indicator of resource productivity recommended for the UK (see Pearce, 2001) is the ratio of output or income (Q) per unit of energy (m), where a rise in this ratio indicates an improvement in the sustainability of economic development. Our model incorporates two variants of this indicator:

- Q/m (1) – GDP (£) per unit of non-electricity energy used (gas, oil or coal), measured in tonnes of oil equivalents
- Q/m (2) – GDP (£) per unit of electricity used, measured in gigawatt hours

Partly due to the problem of determining a common unit of measurement for different types of energy use, a variant on the Q/m indicator of resource productivity is the ratio of output or income (Q) per unit of polluting emissions (e). Again, a rise in this ratio indicates an improvement in the sustainability of economic development. In the model of the UK economy used here we only link one pollutant, CO_2, to energy use, so this indicator is defined as

- Q/e – GDP (£) per tonne of CO_2 emissions

However, an alternative overall indicator of sustainable development[7] is the inverse of this ratio. This is referred to as the 'Sustainable Prosperity' indicator and is defined as the level of CO_2 emissions divided by GDP, or the CO_2 intensity of UK GDP, where a fall in this ratio indicates an improvement in the sustainability of economic development. Thus, we also report

- Sustainable Prosperity – Total CO_2 emissions (in tonnes) per £ of GDP

Finally, we model two indicators identified that focus on the sustainability of energy consumption and production[8]:

- Energy consumption – total use of electricity in Scotland (gigawatt hours)

The broad target for the first of these is that consumption of electricity, particularly from non-renewable sources, should decline.

In terms of reducing levels of emissions of greenhouse gases, including CO_2, while the UK has set firm targets for 20% reductions, in line with its commitments such as the Kyoto Protocol, the Scottish Executive has not. Instead, it has stated the intention to make an "equitable contribution" to the UK Kyoto target for greenhouse gas emissions (Scottish Executive, 2003, p.19).

Database

The main database of UKENVI is a specially constructed Social Accounting Matrix (SAM) for the UK economy. This required the construction of an IO table for the UK for the year 2000, since an appropriate analytical IO table has not been published for the UK since 1995. A twenty-five sector SAM was then developed for the UK using the IO as a major input. The sectoral aggregation (identified in Appendix 2) is chosen to allow a focus on sectors within which there were activities affected by the EU Emissions Trading Scheme.

The information on income transfers that is necessary to expand the IO into a SAM came from a set of Income-Expenditure accounts for the UK in 2000, developed on the basis of single-entry bookkeeping, where any item of expenditure in one account also appears as an item of income in another. Five sets of income-expenditure accounts were constructed for households, corporations, government, capital and the external sector. Full details on the construction of the UK IO table and SAM, together with some descriptive analysis, are given in Appendix 2.

5. Results of the CGE simulations

Simulation strategy

The disturbance simulated using the UKENVI model is a 5 per cent improvement in the efficiency by which energy inputs are used by all production sectors. Recall that the five energy sectors in UKENVI are the coal, oil, gas and renewable and non-renewable electricity. An efficiency shock is introduced in the production of the local composite good. (See Figure 4.1.) This shock is a one-off step change in energy efficiency, which is introduced as a composite energy augmenting type. This introduces a beneficial supply-side disturbance, which would be expected to lower the price of energy, measured in efficiency units, generally reduce the price of outputs and stimulate economic output.

Central case scenario

The size of the impacts on key aggregate variables is shown in Table 5.1. Note that the figures reported are percentage changes from the base year values. The economy is taken to be in equilibrium prior to the energy efficiency improvement and the results are best interpreted as being the proportionate changes over and above what would have happened without the efficiency shock.

Results are for two conceptual time periods: the short and long run. In the short run, capital stocks are fixed at their base year values at the level of individual sectors. In the long run, capital stocks adjust fully to their desired sectoral values, given the efficiency shock and a fixed interest rate. With wage determination characterised by a wage curve, a beneficial supply-side policy, such as an improvement in energy efficiency, would increase national employment, reduce the unemployment rate and increase real wages. However, in UKENVI this tightening of the labour market does not stimulate in-migration. This contrasts with the corresponding Scottish model, AMOSENVI, where inter-regional migration plays an important expansionary factor in similar energy efficiency simulations.

We note that the energy efficiency improvement has a positive impact on UK economic activity and that this is greater in the long run than in the short run. In the long run there is an increase of 0.17% in GDP and 0.21% in employment and exports. The expansion is lower in the short run, where a larger increase in consumption partially offsets a fall in exports.

The energy efficiency improvements primarily increase the competitiveness of energy intensive sectors through a reduction in their relative price. In the long run two mechanisms drive this change in competitiveness. First, the increase in energy efficiency raises the production efficiency of energy intensive sectors by the greatest amount. Second, the production techniques used in energy sectors themselves are typically energy intensive, so that the price of energy tends to fall. For both these reasons, the price of energy-intensive sectors will experience relatively large reductions in price in the long run. However, as we shall see, in the short-run, capacity issues also affect prices, sometimes in a dramatic way. The changes in the short-run and long-run output prices are reported in Figure 5.1.

In the long run, although real and nominal wages rise, the increase in energy efficiency, together with fixed interest rates, is large enough to generate price reductions in all production sectors. However, there are clear sectoral differences that generally reflect the energy intensity of the sector. In the long run, prices in the manufacturing and service sectors show a small decrease, reflecting the relatively low use of energy inputs in these sectors. Within the manufacturing sectors, energy use generally represents a low proportion of the total value of output. This ranges from 0.79 % for electrical and electronics to 4.70 % for iron, steel and casting activities. An even lower energy incidence is found in service sectors (both public and private) where energy inputs range from 0.47 % for health and social work to 1.48 % for distribution and transport.

The largest impact on the price of output comes in the energy sectors themselves. This reflects the production techniques in these sectors. But across the energy sectors, there is clearly a non-uniform response. The larges reductions in price occur in electricity production, with the price in the non-renewable electricity sector falling by more than the price in the renewable electricity sector. This reflects the heavier reliance of the non-renewable sector on energy inputs. In the UK SAM for 2000, the renewable and non-renewable electricity sectors purchase 41 and 52 per cent of their inputs from the combined five energy sectors.

The division of the electricity sector between renewable and non-renewable generation used an experimental disaggregation provided for Scotland. This was adjusted to reflect the different pattern in electricity generation between the UK and Scotland (see Appendix 2). These proportions of energy inputs to the total value of output seem exceptionally high, especially since within this percentage, electricity consumption itself appears to be a major element.

In the short run, fixed capital stocks mean that the marginal cost of production of value added is upward sloping. An increase in the demand for a sector's value added leads, ceteris paribus, to an increase in the price of value added, with a corresponding rise in the capital rental rate in that sector. On the other hand, where the demand for a sector's value added falls, the price will fall, as will the capital rental rate.

One interesting short-run result is that the output price actually increases in most of the non-energy sectors. These are the primary sector, the food and drink sector, and all the service and utility sectors. These price increases can be traced to a high portion of value added to output in these sectors and the fact that in all these sectors there is a slight increase in both the nominal wage (Table 5.1) and the capital rental rate. Therefore, in these cases the increases in factor costs are greater than the reduction in intermediate costs brought about by the improvement in energy efficiency. This partly reflects the very low proportionate energy purchases in these sectors.

On the other hand, the price adjustments in the energy production sectors are quite different. First, both in the short and long run, energy prices fall as a result of the improvement in energy efficiency. Second, the price reduction in the short run is greater than in the long run. Third, these price changes are particularly marked for the electricity generating sectors.

The long-run reduction in energy prices reflects the fact that these sectors have relatively energy intensive production processes, so that increased energy efficiency has a relatively powerful negative impact on their price. In the short run, falls in output demand in these sectors generates falls in the capital rental rate, such that the short-run price reductions are greater than those in the long run. In the electricity generating sectors there are significant falls in the price of their output (down over 20%) in the short run. Over this time period the capital rental rates in the renewable and non-renewable electricity generation sectors fall by 23.76% and 26.18% respectively as the demand for value added in these sectors decreases.

The short- and long-run sectoral changes in output are shown in Figure 5.2. As would be expected, the increased efficiency of energy inputs has expanded the output of all non-energy sectors, with the increase almost always being greater in the long than in the short run. Outputs increase most in those non-energy sectors that have greater energy intensities, notably “iron, steel and casting” and “pulp and paper” where output increases in the long run by 0.67% and 0.46% respectively.

On the other hand, the output of the five energy sectors falls in both the short and long run, and in this case the long-run reduction is greater in all long run than the short run. The large reductions in price in the short run go some way to offsetting the demand fall that occurs in the short run. However note that in both the short and long run, the reduction in output is less than the 5 per cent improvement in energy efficiency.

Unlike the Scottish results (reported in Hanley *et al*, 2006), where the output of energy sectors in Scotland increase in the long run, the output of all energy sectors falls in UKENVI as a result of the improvement in energy efficiency. One possible explanation for these differences is that in comparing the Scottish and UK SAM databases, although the comparable energy sectors had similar cost structures, in terms of their purchases of energy products and value added, the destination of their sales was significantly different.

In particular all energy sectors in the Scottish SAM, with the exception of gas, provided more than 20 per cent of their total output for export, mainly to the rest of the UK (although the coal sector produced 9 per cent of its exports for the rest of the world). The energy efficiency improvement in Scotland lowers the relative price of these energy goods, and so demand for energy goods from outside Scotland increases. However, in the UK SAM the energy sectors show a significantly lower propensity to export, with only the oil processing sector, with 29%, producing more than 2% of its output for export outside the UK. The oil processing sector however, doesn’t rely on energy inputs as highly as the other energy sectors, and so the output of this sector falls – as would be expected under the “conventional wisdom” of energy efficiency improvements.

A central result which can be drawn from this analysis is that rebound is recorded across all energy sectors. No energy sector reduces its output by the full amount of the improvement in energy efficiency, although there are significant differences across sectors, including within the energy sectors. Unlike in the Scottish case, there is no evidence of backfire, where the output of sectors actually rises following the improvement in energy efficiency. The variation across energy sectors can be explained by the differences in the degree to which each sector relies upon energy inputs for production, the share of value added in production and the destination of output of each sector.

The economic and environmental results obtained from UKENVI can be used to calculate the corresponding environmental indicators that can be tracked over time as the economic results change. In this section we report four environmental indicators. These are constructed using UKENVI data that links energy use to CO_2 emissions. The four environmental indicators are:

- the ratio of output to energy used (Q/m), which has two versions,
    - the ratio of output (GDP) to units of non-electricity energy use
    - the ratio of output to units of electricity use
- the ratio of output to CO_2 pollutants
- the ratio of CO_2 pollutants to output (the indicator of "sustainable prosperity" for the Scottish Executive)
- the total consumption of electricity in the UK (in gigawatt hours)

Figure 5.3 reports results from a simulation lasting for 20 periods (years). GDP is larger in all periods than in the base year. Energy consumption, measured in electricity GWh, falls from the start and reaches its long-run equilibrium reduction of 3.15% by around period 7. Thus, there is a rebound effect from the 5 per cent reduction in energy efficiency of the order of 37%. Unlike the case for

Scotland (Hanley *et al*, 2006), no backfire effect (an overall increase in energy consumption resulting from an improvement in energy efficiency) is identified.

The Q/m indicators, relating GDP to both non-electricity and electricity energy use, increase from the base position: energy use is falling as GDP is rising. This implies development that is more sustainable: both these indicators register a positive change in the long run, with GDP divided by electricity units used increasing by around 3.5% while the ratio of GDP to non electricity energy units increases by just over 2%.

Figure 5.4 shows that the initial decrease in energy consumption is matched by a corresponding fall in the level of CO_2 emissions related to the use of energy inputs. These fall by around 2.5% compared to the base year level. The rise in GDP and fall in CO_2 emissions means that the "sustainable prosperity" indicator, the ratio of CO_2 emissions to GDP, falls, while its converse ratio (GDP to CO_2 emissions) increases by 2.82%.

Sensitivity analysis around central case scenario

Our central case results presented in Table 5.1 will be sensitive not just to the base year values in the UK SAM, but also to the choice of parameters for key variables in the UKENVI model, possible recycling of any additional government revenues and the cost of any energy efficiency improvements. In the next three subsections we outline the economic, energy and environmental impacts of varying these assumptions.

Results of varying key elasticities

To quantify the impact that changing these parameters has on the results, we perform sensitivity analysis. In this, we vary the key parameters that were used to derive the central case results. The parameters that we would be expected to impact most strongly on the results are the elasticity of substitution between both energy and non-energy intermediate inputs (the SIGMAL parameter), and between value added and intermediate inputs (the SIGMAD parameter). In the central results, both these parameters have an elasticity of 0.3. For sensitivity, we vary these parameters (independently) to 0.1 and 0.7. Another potentially important parameter is the elasticity of export demand. In the central results, this parameter was set at 2 for the non-energy and the non-electricity energy sectors and 5 for the electricity sectors. For sensitivity, these export demand elasticities are varied in a number of ways.

Table 5.2 shows the long run results from varying the elasticity of substitution between energy and non-energy intermediate inputs and the central case scenario. As would be expected, the higher the elasticity, reflecting a greater responsiveness between energy and non-energy inputs, results in a higher GDP impact. Making it easier for sectors to substitute energy for non-energy inputs will lead to bigger price reductions. Conversely, lowering the elasticity of substitution prevents sectors from making this substitution, and so lessens the GDP gain. The GDP results vary from 0.16% in the low elasticity case to 0.18% when the elasticity of substitution is higher.

Intuitively, total energy consumption and rebound effects will be sensitive to the value of this parameter. We would expect that total energy consumption would decline least when it is easier to substitute towards the now relatively cheaper energy inputs. The results presented in Table 5.2 show that total energy consumption declines by over 3.7% in the low elasticity case, while it only declines by 2% in the high elasticity case. The high elasticity case produces a rebound effect of 60.1%, while, with low elasticities, rebound is 25.6%. As can be seen in Figure 5.5, the fall in energy consumption is smallest, across all the sensitivity analysis we carry out when this elasticity of substitution between energy and non-energy inputs is high. Figure 5.8 also shows that total CO_2 emissions from fuel use are reduced from the base year level by only 1.35%.

Table 5.3 shows the long-run results from varying the elasticity of substitution between value added and intermediate inputs. This is the point at the very top level of the production hierarchy used in UKENVI (see Figure 4.1). In the low elasticity case, it is more difficult for sectors to move away from the now relatively more expensive value added composite, and towards intermediate inputs (including the energy inputs) that have experienced a fall in their relative price as a result of the improvement in energy efficiency. In the high case it can be seen that increasing the ease of substitution towards the now cheaper intermediate inputs slightly lowers the GDP effect (from 0.17% to 0.15% above the base year), and produces a smaller overall effect on employment (down from 0.21% in the central case to 0.20%). Here, energy inputs are substituted in favour of labour and capital inputs.

Table 5.3 and Figure 5.5 also show that total energy consumption displays significant rebound effects again, which are greater (56.4%) the higher the value of the elasticity of substitution between value added and intermediate inputs. Rebound is only 27.5% in the low elasticity case. Value-added and employment are thus inversely related to this substitution elasticity, while the extent of rebound is positively related, reflecting the greater degree of substitution towards energy. The impact on GDP and employment are not very sensitive to the elasticity of substitution between value added and intermediate inputs (Figure 5.6 and Figure 5.7), but the impact on CO2 emissions from fuel use (Figure 5.8) is sensitive. These emissions fall by 2.96% in the low elasticity case, but only 1.86% in the high elasticity case.

Table 5.4 shows the long run effects and the central scenario results from varying the export demand elasticities as suggested above. In the base case, these demand elasticities were set at 5 for the two electricity sectors (E), and 2 for the other energy sectors (O) and the non-energy sectors (N). To see the impact of varying these parameters, the 5% energy efficiency shock was repeated with three further scenarios: all sectors' (E, O and N) export demand elasticities set at 2; the export demand elasticity set at 5 for all energy sectors (E and O) and 2 for all non-energy sectors (N); and the export demand elasticities across all sectors (E, O and N) set at 5.

As the elasticity of export demand is increased, sales to exports expand as a result of the greater responsiveness to the UK price reductions. However, the impact of varying these elasticities is fairly modest. This is primarily because those sectors that have the largest reduction in price are primarily the energy sectors that, in the main, do not export in the UK case.

Varying this parameter appears to have little impact on the results in terms of GDP, employment, energy use, emissions and the estimated rebound effect. GDP increases range from 0.17% with all export demand elasticities set at 2, to 0.19% with all elasticities at 5. The variation in total energy consumption is also small, with the rebound effect only ranging from 36.4% to 37.7%. This result suggests that in the specific case of the model of the UK, the elasticity of export demand appears to be comparatively unimportant for the overall degree of rebound in energy use, no doubt reflecting the current structure of the UK market.

Results of enforcing government budget constraint

Another potentially important feature of the central case projection is the treatment of the government sector. In the central case and all sensitivity simulations performed up to now, the improvement in energy efficiency stimulates aggregate economic output and employment. Given fixed average tax rates, there will be an increase in the tax revenues of the UK government and a reduction in social security spending. In our central case, the government saves all of this improvement to its budgetary position. This increased government revenue can however be recycled back to the economy through enforcing an active government budget constraint (modelled in UKENVI as maintaining the base year ratio of government savings to GDP).

In the UKENVI model the government budget constraint can be imposed in two ways. These have quite different economic impacts. First, additional revenue can be used to expand general government expenditure, distributed across sectors using the base-year weights. Second, extra revenues received can be recycled back to households through reduced income tax. The long run impacts of these two scenarios, plus the central case where extra revenues are not recycled, are shown in Table 5.5.

When the additional tax revenues are recycled as extra government expenditure, this acts as an exogenous demand injection and stimulates GDP and employment. The sectoral changes in output are focused on government sectors, as would be expected. In the second scenario however, when increased revenues are recycled in the form of a decreased income tax rate, there are significantly larger impacts.

The recycling of the extra government tax revenues through changes in the rate of income tax can be viewed as having both supply and demand impacts. On the demand side lowering the tax rate will raise take home wages, and thus will stimulate demand. There will also be a supply-side impact as the labour market is characterised by a bargained real wage. A fall in the income tax rate means that a lower nominal wage is needed to maintain a given real take-home wage. This makes substitution towards labour more attractive, which boosts employment. This can be seen by the smaller increase for the nominal real wage in Table 5.5 where income tax adjusts, against when government expenditure changes. The level of employment also increases significantly between these two results (0.26% higher than the base case when government expenditure adjust, against 0.38% higher when income tax rates adjust – see Figure 5.7), reflecting the impact of the relatively cheaper labour inputs compared to when government expenditure adjusts. There is also a significant GDP impact in both cases, but especially strong when income tax rates adjust (raising GDP by 0.34% against 0.20% when total government expenditure adjusts).

The energy and environmental results are also slightly different under these two scenarios. Total energy consumption actually falls by less (as compared to the central scenario) when government expenditure adjusts, reflecting the switch towards less energy intensive government demands, and increased employment in public sectors. Total energy consumption falls by 3.17%, indicating a rebound effect of some 36.7%. When income tax rates adjust however, the demand and supply side impacts produce a smaller decrease in energy use, and a rebound effect of 41.8%.

Results of implementing a costly energy efficiency policy

Our assumption up to this point has been that energy efficiency improvements are like "manna from heaven" – a costless benefit. We here simulate the possibility that making gains in energy efficiency would result in costs borne by production sectors. We model the same 5% improvement in energy efficiency across all sectors, but simultaneously capture a cost to the efficiency of labour inputs in production. This can be thought of as representing the additional costs to labour to implementing the improvement in energy efficiency.

The size of the negative shock in each sector was imposed such that with no change in prices, the increase in costs implied by the reduced labour efficiency just equals the reduction in cost implied by the 5% improvement in energy efficiency. The change in labour efficiency in sector I (λ_i) is estimated as:

$$\lambda_i = 0.05\left[\frac{E_i}{L_i}\right]$$

where E_i and L_i are the base year expenditures on energy and labour in sector i. We consider this to be the upper bound of the costs of energy efficiency improvements.

The aggregate results from introducing both the positive energy efficiency improvement and the negative shock to the production of labour inputs, are shown in the final column of Table 5.6. The negative efficiency shock to labour, combined with the positive energy efficiency gain, leads to a very small increase in total employment over the base year case, and a fall in GDP (See Figure 5.6 and Figure 5.7 for the dynamic path of these series). Up to now we have been assuming a costless improvement in energy efficiency. However, we can consider the results reported in the final column of Table 5.6 to be the most extreme example of a "costly" energy efficiency improvement, in that the net impact is broadly cost neutral to individual industries. We would expect actual energy efficiency improvements to lie somewhere between these two extremes.

The changes in energy use from the simulation of this costly energy efficiency policy are significantly different to most other sensitivity results carried out thus far. Total energy consumption falls in the long-run by 4.132%, indicating a rebound effect of 17.4%. Introducing significant costs to implementing energy efficiency improvements thus prevents a significant switch towards the output of more energy intensive sectors output, thus releasing a larger share of the stimulus to energy efficiency in the form of energy savings. Significantly however, this smaller rebound effect is achieved at a cost in terms of GDP, although with a slight increase in total employment. Total CO_2 emissions from fuel use in this scenario also fall, by 3.76%. Thus, even when implementing energy efficiency improvements carries a cost, total energy reductions in CO_2 emissions from fuel use do not fall by the 5% improvement in energy efficiency.

Since the above "costly policy" simulation assumes that the improvement in energy efficiency is fully offset by a negative efficiency effect to labour efficiency, this can be considered to be a limiting case of the costs to implementing an improvement in energy efficiency. The results of two further sensitivity simulations are reported in the second and third columns of Table 5.6. In the first of these simulations, one-third of the cost savings from energy efficiency improvements are incurred as negative costs to labour efficiency, while in the second, two-thirds of these cost savings are spent realising the cost savings. These are intended to be illustrative of the range of results as the cost of implementing the policy changes.

The scale of the rebound effect is sensitive to the scale of the policy cost, showing interim stages of 31.3 and 24.8% rebound. Interestingly, the GDP impact is positive (up 0.019% from the base year) where one-third of the efficiency impact is offset by additional labour costs.

Results from different labour market closures

We know that assumptions about labour market behaviour can have a major impact on the macroeconomic effects of any disturbance. In each of the simulations reported above we have assumed that the supply side of the labour market can be characterised by a bargained real wage function in which the real consumption wage is directly related to workers bargaining power, and inversely to the unemployment rate. Two other specifications of the labour market, as introduced in Section 4, are be considered here. First, we impose an exogenous labour supply function, in which there is, in effect, a completely wage-inelastic aggregate labour supply function so that aggregate employment is effectively fixed. This is quite a common assumption in national CGEs, but seems unduly restrictive. We also impose a real wage resistance closure, in which the real wage is exogenous at the prevailing real wage, and employment adjusts to ensure equilibrium. These can be considered as two limiting cases capturing zero and infinite-elasticity of labour supply with respect to the real consumption wage.

The aggregate results in the short and long-run from introducing a 5% energy efficiency improvement are shown in Table 5.7. In the exogenous labour supply scenario there is, as would be anticipated, a significant increase in real take-home wages, however there is also a small decrease in GDP in each time period. Total energy consumption declines in each simulation, with rebound of 50.6% in the short run falling to 32.9% when capital stocks have adjusted fully. In the real wage resistance case, GDP rises in both the short (0.225%) and long run (0.897), and, as would be expected there is a substantial increase in overall employment (of over 4 times that in the central scenario). Total energy consumption again displays rebound in both time periods, but the reduction between the short run (55.3%) and the long run (51.7%) is small compared to the other sensitivity analysis results presented here. As can be seen in Figure 5.5, the reduction in energy use is greatest around period 5, but energy use relative to the central scenario increases after this point.

The ratio of GDP to CO_2 emissions (and its inverse) is shown for all the sensitivity analysis detailed above in Figures 5.9 and 5.10. The rank order of these impacts is largely similar to that for the reductions in total CO_2 emissions from fuel use. Figures 5.11 and 5.12 show the changes in the ratio between GDP and energy (non-electricity and electricity, respectively) for the central case and the different sensitivity simulations.

6. Policy implications

Our own theoretical analysis, building on that of e.g. Saunders (2000a), implies that a rebound effect from an improvement in the efficiency with which energy enters the production functions of firms/households in an economy is *to be expected* from the point of view of neo-classical production and growth theory. Energy-augmenting technical progress causes firms to wish to use more energy (measured in efficiency units). This is the substitution effect, as the price of energy, in efficiency units, has fallen. Second, the efficiency gain increases output by reducing costs and stimulating competitiveness, thereby stimulating energy use. This is the output effect. This effect may be especially noticed in highly-open economies, where energy intensive goods are exported, since international competitiveness improves. Third, in a multi-sectoral world, a composition effect occurs whereby products which are relatively energy-intensive in production fall in cost relative to those which are less-energy intensive. These three effects operate throughout the domestic economy, and mean that the reduction in aggregate fuel use, and thus the improvement in Y/m type measures, is likely to be less than that which we would predict from the simple improvement in technical efficiency (rebound) and may be strong enough to overwhelm this simple effect, pushing our resource productivity and sustainability indicators in the wrong direction (backfire). The only kind of economy where rebound would be unexpected is one in which all demands, as well as technologies take the Leontief form, so that there is no system-wide sensitivity to relative price changes. This is a limiting case that we cannot conceive of any real world economy conforming to.

Rebound and backfire are of considerable potential relevance to climate change policy, since the coupling of reductions in energy use with no penalty in terms of output (the “zero-cost” ideal of the resource productivity enthusiasts) may not in fact be the win-win option suggested, due to induced effects on output and the consequent scale effect on environmental burdens. Rebound does undoubtedly imply that the environmental gain generated by an improvement in energy efficiency is less than a simple engineering approach (which embodies zero rebound) would imply. However, it is important to appreciate that this reflects the presence of an economic gain that would be similarly unrecognised by a simple engineering approach. The presence of such economic gains when rebound and backfire are present at least suggests the potential for a welfare-improving policy adjustment. However, without such an adjustment, rebound and backfire do imply a fall in environmental quality relative to the zero rebound engineering case.

The rebound effect is therefore something that policy makers should be aware of, in terms of both the design of energy policy, and in its evaluation. We now discuss some issues related to these two contexts.

Issues Arising for the Design of Energy Policy

Our work shows that energy efficiency measures would generally be expected to generate a less than proportional fall in energy use (rebound), and may actually stimulate its use (backfire). Our own view is that even the presence of backfire does not undermine the case for energy efficiency policy: although it does imply that environmental benefits cannot be guaranteed by such policies alone. Rebound implies that environmental improvements will not be as great as the initial percentage fall in energy use per unit output. However, the extent of rebound is ultimately an empirical issue. Our own empirical analysis suggests the likelihood of significant rebound effects in response to system-wide changes in energy efficiency (of the order of 40%) for the UK as a whole. However, there is an accompanying stimulus to economic activity. A clear policy implication is thus that: (i) in general, the coordination of energy policies would be beneficial and (ii) that an increased energy tax may be required to be implemented alongside the energy efficiency improvement. Roy (2000) notes this in the context of a developing country (India), but it is also relevant to the current context. This implies a need for the government to track energy efficiency changes for every sector of the economy.

Our results show some sensitivity of the rebound effect to changes in the parameter values for the elasticity of substitution between energy and non-energy intermediates; and for the elasticity of demand for energy, electricity and non-energy sectors. However, it is difficult to see how energy policy could in itself do much to change these parameters in the "right" direction. Substitution possibilities at the general equilibrium level depend on the complex interaction over time of technological production conditions, preferences and prices – and so it would be hard for government policy to try to bring about particular changes in these substitution possibilities. It would, in any case, be a rather odd policy that sought to reduce flexibility of response in an economy, which is another way of thinking about substitution elasticities. Indeed, improvement of information flows and reduction of transactions costs would be likely to increase effective elasticities, not reduce them.

We also note that in our simulations, the energy efficiency effect boosts government revenues, since these are positively correlated with GDP and income. If the government wishes the energy efficiency improvement to be revenue-neutral, then it can either recycle government revenues through increased expenditure or reduce average tax rates. In our simulations, a general stimulus to government expenditure or a reduction in the average income tax rate both stimulate the economy, but by more in the latter case because of the strength of beneficial supply side impacts. The overall rebound effect is hardly affected by the recycling through increased expenditures, but is slightly increased in the other case due to the consumption stimulus. In general environmental impacts will depend crucially on precisely how the government budget is closed. For example, cutting other environmental taxes would increase overall environmental burdens, and this is also be true for cuts in income tax (e.g. if consumer expenditure is more energy-intensive than government expenditure). Higher government spending on R&D in renewable technology, or on infrastructure for hydrogen vehicles or on low-emission trains, would reduce the *environmental* rebound associated with energy efficiency gains, driving down CO_2 emissions over time. If off-setting increases in government spending impact on environmental indicators other than those relevant to climate policy (e.g. impacts on water quality), then we need to know how substitutable gains in one environmental target area are for losses in another.

Finally, energy efficiency improvements are likely to be the result of conscious R&D investments, rather than emerging exogenously. How government behaves in terms of incentivising endogenous technological change for energy-using processes will be crucial. That government has a role in doing this comes from a recognition of the public good aspects of technological change.

Evaluation issues for energy policy

Given what has been presented above, it is important that, where substantial across-the-board energy efficiency improvements are being pursued, future evaluation work of adopts an approach which allows the system-wide effects of efficiency improvements to be assessed. This should include a comprehensive linkage of economic activity in both the production and consumption sectors with environmental impacts such as changes in emissions of main pollutants. Changes in environmental impacts will come about both directly, through a reduction in energy use per unit of output, but also indirectly in terms of substitution, output and composition effects, as noted above. For example, the competitiveness boost to GDP could result in rising levels of conventional air pollutants such as TSP due to a rise in road freight traffic or air travel. The system used should also allow the analyst to analyse the effects on sustainability indicators such as the GDP/CO_2 ratio in both the short run and longer term.

Such an approach also allows the analysis to reflect the operation of a stimulus to GDP, employment and incomes resulting directly from the increase in energy efficiency. A full Cost Benefit Analysis of efficiency effects would need to take these knock-on macro effects into account. The analysis should also be undertaken at fairly disaggregated level, since rebound effects have been found with very different magnitudes for different sectors (for example, Grepperud and Rasmussen (2004) find large effects in manufacturing, but little effects in other sectors of the Norwegian economy, whilst in their study the rebound effect was dramatically different in metal manufacturing compared to pulp and paper manufacture).

One important point in evaluating the macroeconomic impacts of a resource productivity change is to know whether it is a one-off shock, or a continuous process. While a one-off shock is capable of having impacts on GDP (moving it to a new equilibrium over time), only a continuous process of improvement will change the growth rate of the economy. Changing the growth rate clearly implies a much bigger economic benefit or cost than a change in equilibrium output.

Another key question to be asked in monitoring the effects of energy efficiency improvements is whether the productivity of other inputs has been changed by the energy efficiency shock. Saunders (2000a) gives the example of steel making in the US, where energy efficiency improvements have also resulted in an increase in both labour productivity and capital productivity. This could in turn increase output in other sectors, which reinforces the rebound effect as it pulls up energy demand economy-wide.

CGE modelling makes it simpler to evaluate the *net* impacts of energy, climate or technology policy on energy efficiency since it makes very clear what the "counter-factual" is. This counter-factual is the base-line run of the model without the change in energy efficiency. All changes in pollution, output, and employment which are observed from the technology shock are then measured relative to this baseline. This makes the marginal effects of technology change clear. However, evaluating the same policy using time series or cross-sectional statistical data requires us to be able to identify the counter-factual by appropriate statistical control. This may be much harder, and therefore more likely to risk confusing the actual drivers of changes in resource use and pollution. Of course, results are conditional upon model structure and the context of its implementation. The contrast between the "backfire" apparent in our application to Scotland and the "rebound" effect we find in the

UK emphasises the importance of this, with Scotland being more open, in terms of price elasticities of demand and the importance of migration flows and it being a significant net exporter of electricity.

It is also desirable that, in the case of the use of time series or cross-section data to analyse the effects of changes in energy efficiency, that a distinction be drawn between price-induced change and technology-induced change. The US economy underwent many changes as a result of the real oil price increases of the early 1970s in terms of how it used energy: however, price-induced efficiency change comes at a macro cost (eg higher inflation, or lower output). Technology driven energy efficiency comes, in principle, at no cost to the economy, and can even (in fact, is likely to) result in higher output. Distinguishing between these two drivers is important, as Hogan and Jorgenson (1991) have argued, especially in the context of climate change policy.

7. Conclusions

In this report we explore the impact of improvements in resource productivity both theoretically and empirically using a flexible, energy-economy-environment CGE framework. We have argued that predicting the environmental impacts of significant improvements in resource productivity requires this general equilibrium approach, since we would expect such improvements to generate important system-wide output and substitution effects that tend to increase resource use, and act as countervailing influences to the direct effects of being able to "produce more with less". We sought to clarify the theoretical literature on rebound and backfire effects according to which energy efficiency enhancement may be partially, or even completely, ineffective in reducing energy consumption. In the present case, we find evidence of a significant rebound in the UK economy (of slightly less than 40% in the central case). The extent of rebound varies, as we would expect, with the substitution and demand elasticities within the system, and, in particular, increase as it becomes easier to substitute energy for other inputs.

The presence of rebound does, of course, imply a smaller environmental gain from energy efficiency improvements than would be implied by a simple engineering approach. But equally, this reflects the presence of an economic gain to that the simple engineering approach would not identify. The stimulus to activity improves tax revenues, which may be recycled to stimulate government expenditure or reduce the average tax rate. The economic gain is increased in both cases, though more so when the tax rate is adjusted, but the extent of rebound also increases slightly in this case. While these results are not what advocates of enhancing resource productivity would necessarily anticipate, or wish for, it is potentially important for the appropriate conduct of energy policy.

Two important caveats are, however, in order. First, our results are, of course, conditional upon the model's structure and the values of key parameters, which are not typically estimated. Our sensitivity analysis in the UK context, however, suggests that backfire is unlikely even with very high substitution and demand elasticities. Nonetheless, the importance of this point is very clearly apparent from a comparison of the results we obtained from Scotland with those we obtained for the UK, using a model of virtually identical broad structure. Secondly, the household demand side of the system is comparatively inflexible with the notable exception of transactors' responses to trade flows. This reflects a more general presumption of limited household substitution possibilities.

We believe that the key point that this report makes is an interesting one: focussing on improvements in resource productivity as a keystone of sustainability policy may produce undesirable impacts in terms of pollution generated within particular regions. Our results also provide a cautionary note on the potentially crucial importance of adopting a system-wide framework to explore the impact of policy initiatives (although the efficiency stimulus that we analyse here is taken to be exogenous). Policies may have important unintended effects, which can mitigate their efficacy in achieving particular objectives.

We end by noting that we do not regard our analysis as providing a damning critique of policies designed to enhance energy efficiency, as advocacy of the potential importance of significant rebound and backfire effects appears typically to be interpreted. We adopted this position even in respect of our findings of backfire in the Scottish case. (Such policies would, though, have to be modelled explicitly if they are to be properly evaluated - something we intend to pursue in future research - and are not, of course, captured by the exogenous technical change that is the focus of this paper, and of many others in this literature.) Rather, our analysis serves to emphasise that such policies certainly cannot, in general, be relied upon on their own to deliver reductions even in the energy intensity of production, let alone to secure a fall in the absolute level of pollutants of the type that is required, for example, by the Kyoto agreement for greenhouse gasses. However, the UK evidence suggests that energy efficiency stimuli do have a beneficial impact in reducing energy consumption to the extent of more than 60% of any efficiency gain.

Improvements in energy efficiency do create the potential for energy taxes to be levied without generating any of the adverse effects on economic activity that would otherwise be expected, particularly in the absence of revenue recycling. In this sense we would fully endorse Birol's and Keppler's (2000) view, that technology and relative price policies should be regarded as complementary. The appropriate combination of energy taxes (especially with revenue recycling to reduce taxes on employment) and energy efficiency stimuli, offer the potential of a genuine "double dividend" of simultaneous economic and environmental gain. However, while these potential gains are available in principle wherever energy efficiency is enhanced, their realisation necessitates conscious and coherent co-ordination of energy policies.

Figure 4.1: Production structure of each sector i in the 25 sector/commodity UKENVI framework

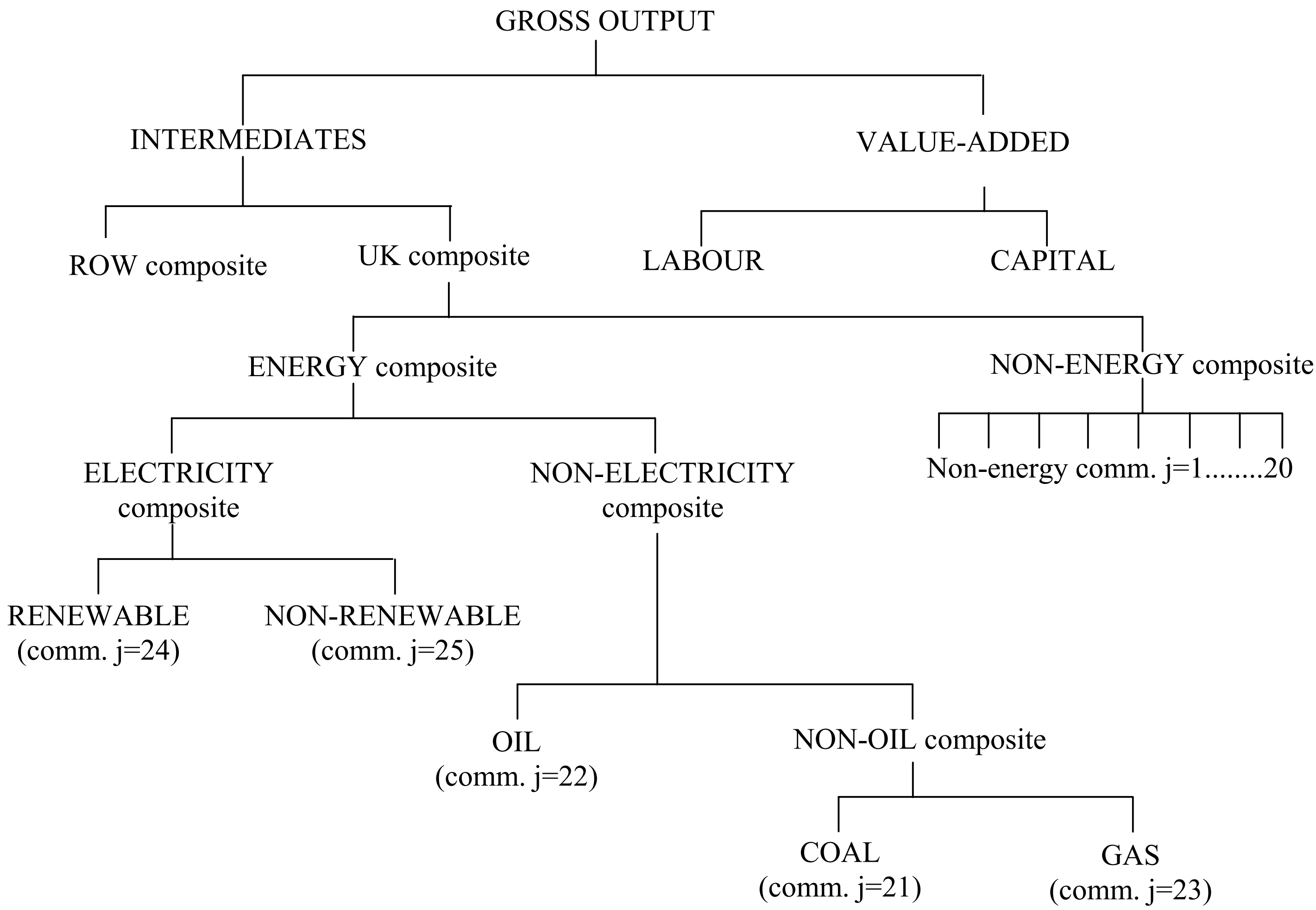


Table 5.1 The aggregate impact of a 5% increase in energy efficiency in all production sectors (percentage changes from the base year)

	Short-run	Long-run
GDP (income measure)	0.105	0.168
Consumption	0.365	0.342
Investment	0.062	0.135
Exports	-0.027	0.214
Imports	-0.226	-0.210
Nominal before tax wage	0.010	0.069
Real take-home consumption wage	0.280	0.300
Consumer price index	-0.269	-0.230
Total employment	0.195	0.208
Unemployment rate (%)	-2.441	-2.612
Total population	0.000	0.000
Total energy consumption (in GWh)	-2.349	-3.149
Rebound effect (%)	53.02	37.02

Figure 5.1 The change in the price of output from a 5% improvement in energy efficiency

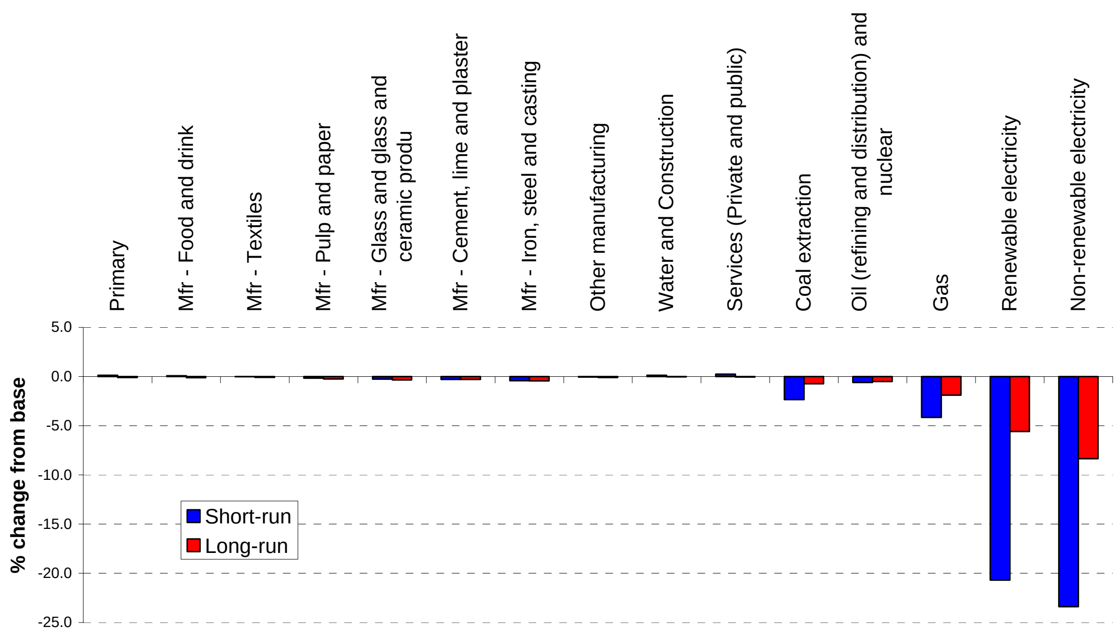


Figure 5.2: Change in sectoral output from a 5% improvement in energy efficiency

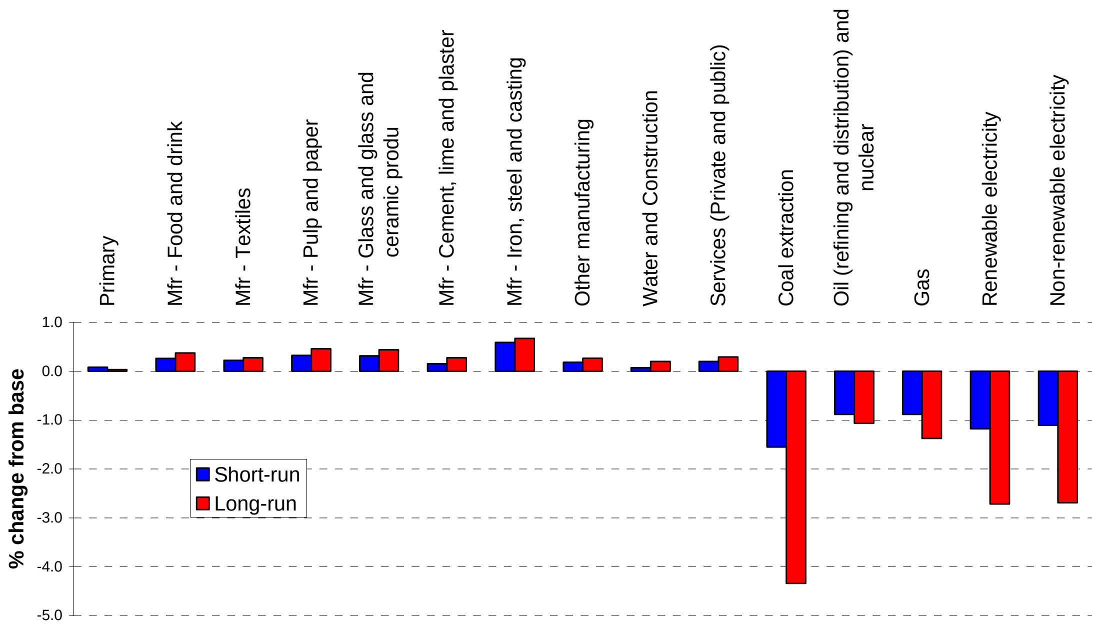


Figure 5.3 Impact on Q/m, GDP and energy consumption indicators from a 5% increase in energy efficiency in the UK

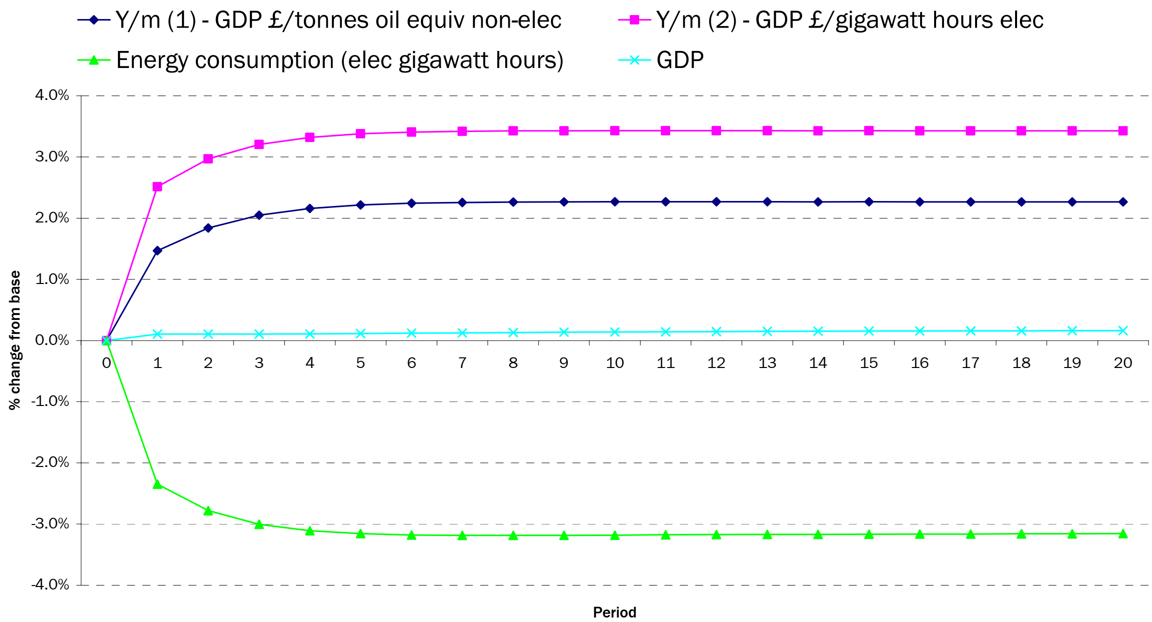


Figure 5.4 Impact on environmental indicators in response to a 5 per cent increase in energy efficiency in the UK

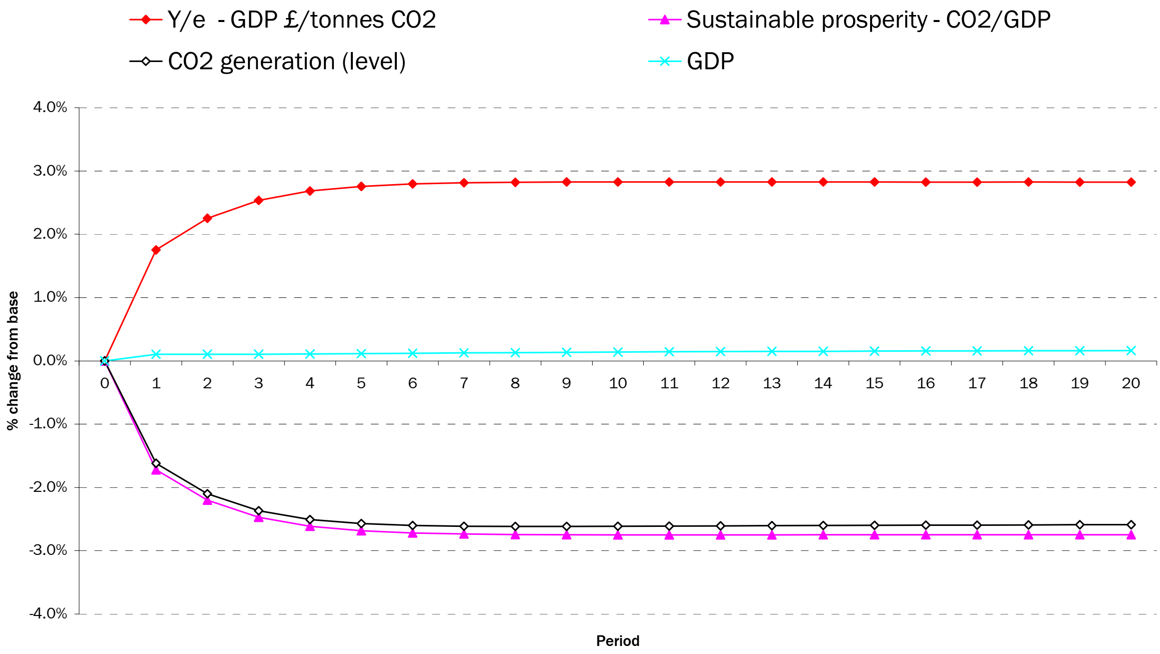


Table 5.2 Impact of changing elasticity of substitution between energy and non-energy intermediate inputs (the SIGMAL parameter) (percentage changes from base year)

	Low (0.1)	Central (0.3)	High (0.7)
GDP (income measure)	0.162	0.168	0.181
Consumption	0.337	0.342	0.351
Investment	0.119	0.135	0.167
Exports	0.209	0.214	0.239
Imports	-0.209	-0.210	-0.210
Nominal before tax wage	0.076	0.069	0.054
Real take-home consumption wage	0.302	0.300	0.295
Consumer price index	-0.225	-0.230	-0.240
Total employment	0.210	0.208	0.205
Unemployment rate (%)	-2.631	-2.612	-2.574
Total population	0.000	0.000	0.000
Total energy consumption (in GWh)	-3.720	-3.149	-1.993
Rebound effect (%)	25.6	37.0	60.1

Table 5.3 Impact of changing the elasticity of substitution between value added and intermediate inputs (the SIGMAD parameter) (percentage changes from base year)

	Low (0.1)	Central (0.3)	High (0.7)
GDP (income measure)	0.177	0.168	0.150
Consumption	0.350	0.342	0.326
Investment	0.150	0.135	0.103
Exports	0.198	0.214	0.258
Imports	-0.215	-0.210	-0.199
Nominal before tax wage	0.086	0.069	0.037
Real take-home consumption wage	0.305	0.300	0.289
Consumer price index	-0.218	-0.230	-0.252
Total employment	0.212	0.208	0.201
Unemployment rate (%)	-2.658	-2.612	-2.525
Total population	0.000	0.000	0.000
Total energy consumption (in GWh)	-3.625	-3.149	-2.181
Rebound effect (%)	27.5	37.0	56.4

Table 5.4 Impact of changing the export demand elasticity (the RHOUK AND RHOW parameters) (percentage changes from base year)

Export demand elasticities for sectors*	E=5 O=2 N=2	E=2 O=2 N=2	E=5 O=5 N=2	E=5 O=5 N=5
GDP (income measure)	0.168	0.167	0.174	0.191
Consumption	0.342	0.341	0.347	0.368
Investment	0.135	0.132	0.146	0.164
Exports	0.214	0.215	0.238	0.341
Imports	-0.210	-0.212	-0.193	-0.100
Nominal before tax wage	0.069	0.067	0.077	0.134
Real take-home consumption wage	0.300	0.299	0.303	0.326
Consumer price index	-0.230	-0.231	-0.225	-0.191
Total employment	0.208	0.208	0.210	0.226
Unemployment rate (%)	-2.612	-2.607	-2.639	-2.835
Total population	0.000	0.000	0.000	0.000
Total energy consumption (in GWh)	-3.149	-3.180	-3.144	-3.114
Rebound effect (%)	37.0	36.4	37.1	37.7

*Note: E = electricity sectors, O = other energy sectors and N = non-energy sectors

Table 5.5 Impact of recycling government revenues through adjusting government expenditure or adjusting income tax (percentage changes from base year)

	No budget constraint	Government expenditure adjusting	Income tax adjusting
GDP (income measure)	0.168	0.203	0.342
Consumption	0.342	0.396	0.694
Investment	0.135	0.133	0.329
Exports	0.214	0.012	0.188
Imports	-0.210	-0.023	0.028
Nominal before tax wage	0.069	0.242	0.094
Real take-home consumption wage	0.300	0.369	0.549
Consumer price index	-0.230	-0.127	-0.215
Total employment	0.208	0.256	0.377
Unemployment rate (%)	-2.612	-3.207	-4.730
Total government expenditure	0.000	0.605	0.000
Total energy consumption (in GWh)	-3.149	-3.165	-2.911
Rebound effect (%)	37.0	36.7	41.8

Table 5.6 Impact of introducing a simultaneous improvement of 5 per cent in energy efficiency and a negative shock to technical progress (percentage changes from base year)

	No cost to implement efficiency improvement	One-third of efficiency impact offset by additional labour costs	Two-thirds of efficiency impact offset by additional labour costs	Efficiency impact fully offset by additional labour costs
GDP (income measure)	0.168	0.019	-0.141	-0.333
Consumption	0.342	0.228	0.104	-0.044
Investment	0.135	-0.001	-0.147	-0.319
Exports	0.214	0.073	-0.080	-0.254
Imports	-0.210	-0.181	-0.146	-0.094
Nominal before tax wage	0.069	0.106	0.148	0.207
Real take-home consumption wage	0.300	0.222	0.137	0.035
Consumer price index	-0.230	-0.115	0.012	0.172
Total employment	0.208	0.155	0.096	0.025
Unemployment rate (%)	-2.612	-1.941	-1.201	-0.308
Total population	0.000	0.000	0.000	0.000
Total energy consumption (in GWh)	-3.149	-3.437	-3.759	-4.132
Rebound effect (%)	37.0	31.3	24.8	17.4

Note: The “costly policy” sensitivity in Figure 5.5 to 5.12 relate to the simulation in the final column here above.

Table 5.7 Impact of changing the specification of the labour market (percentage changes from base year)

	Bargaining		Exogenous Labour Supply		Real Wage Resistance	
	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run
GDP (income measure)	0.105	0.168	-0.019	-0.037	0.225	0.897
Consumption	0.365	0.342	0.299	0.213	0.428	0.799
Investment	0.062	0.135	-0.151	-0.070	0.268	0.862
Exports	-0.027	0.214	-0.193	-0.034	0.133	1.119
Imports	-0.226	-0.210	-0.240	-0.173	-0.212	-0.337
Nominal before tax wage	0.010	0.069	0.370	0.281	-0.388	-0.676
Real take-home consumption wage	0.280	0.300	0.569	0.385	0.000	0.000
Consumer price index	-0.269	-0.230	-0.198	-0.103	-0.388	-0.676
Total employment	0.195	0.208	0.000	0.000	0.383	0.949
Unemployment rate (%)	-2.441	-2.612	0.000	0.000	-4.804	-11.878
Total population	0.000	0.000	0.000	0.000	0.000	0.000
Total energy consumption (in GWh)	-2.349	-3.149	-2.468	-3.357	-2.234	-2.413
Rebound effect (%)	53.0	37.0	50.6	32.9	55.3	51.7

Figure 5.5 Impact on total energy consumption for central case and sensitivity analysis

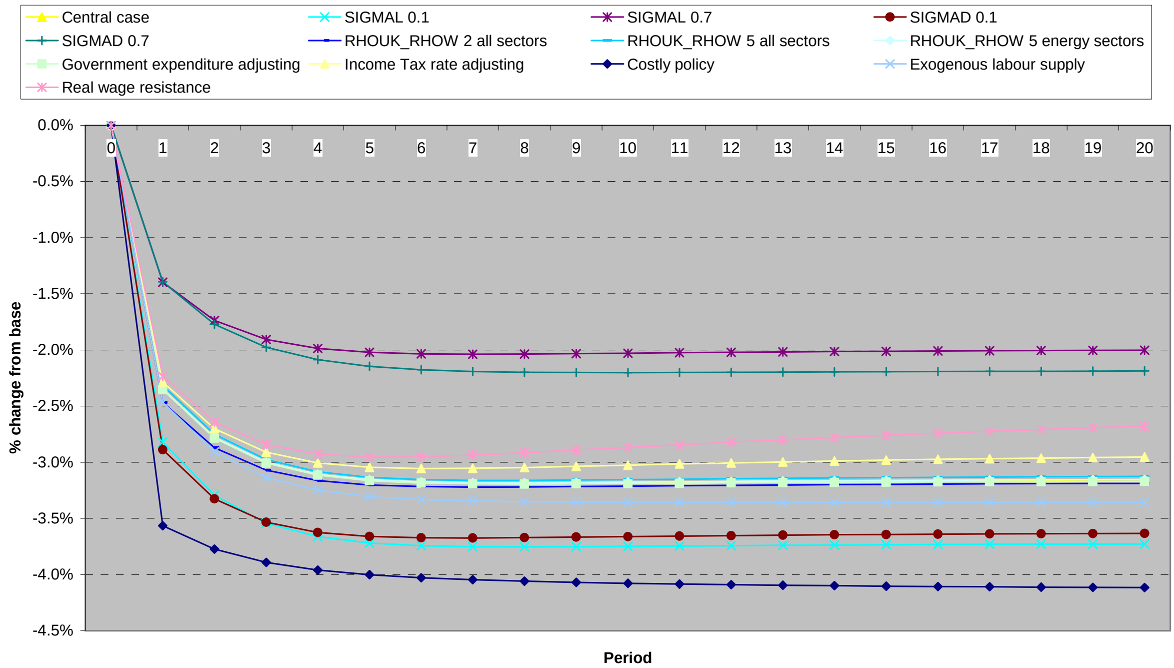


Figure 5.6 Impact on GDP for central case plus sensitivity analysis

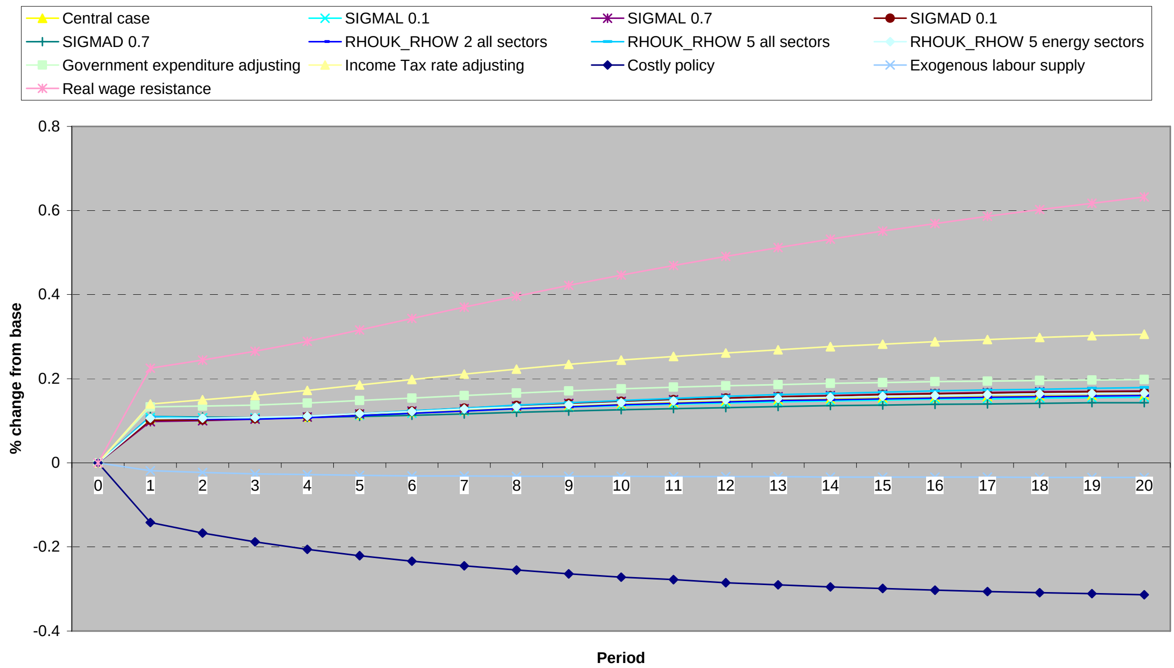


Figure 5.7 Impact on employment for central case plus sensitivity analysis

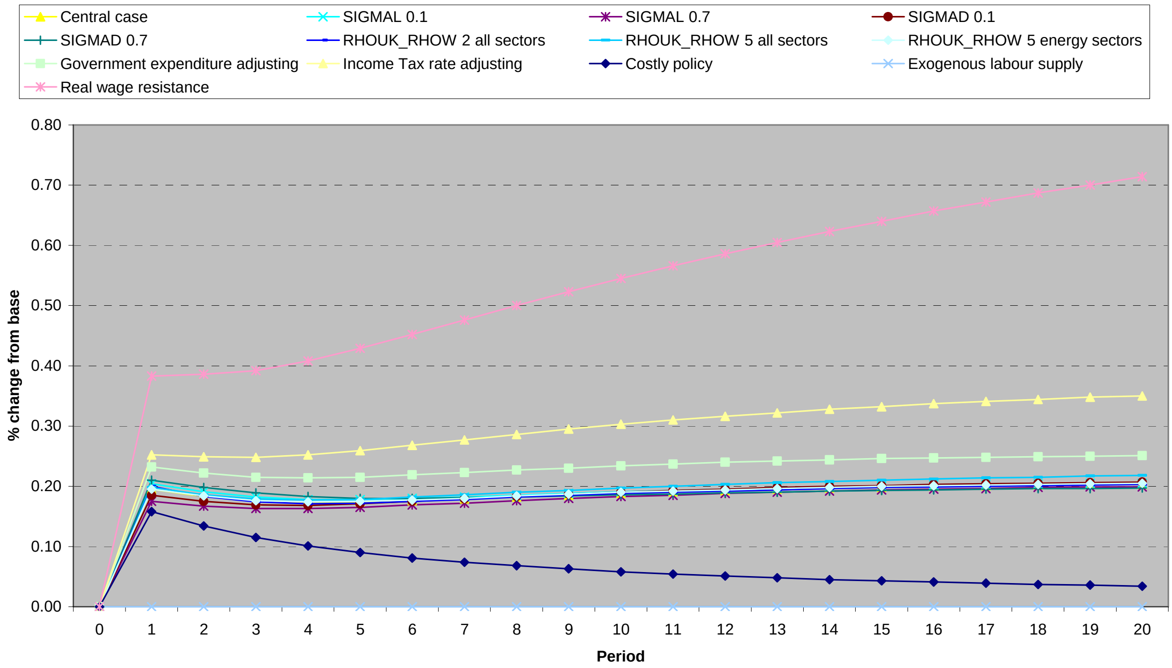


Figure 5.8 Impact on CO2 emissions from fuel use for central case and sensitivity analysis

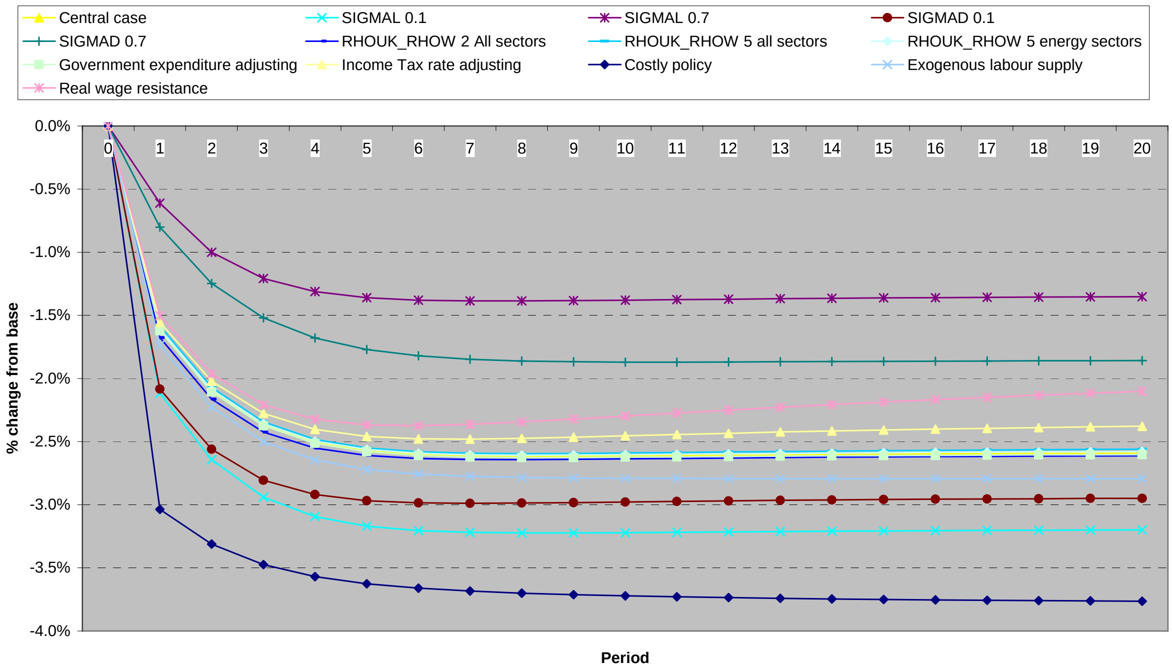


Figure 5.9 Impact on GDP/CO2 emissions from fuel use for central case and sensitivity analysis

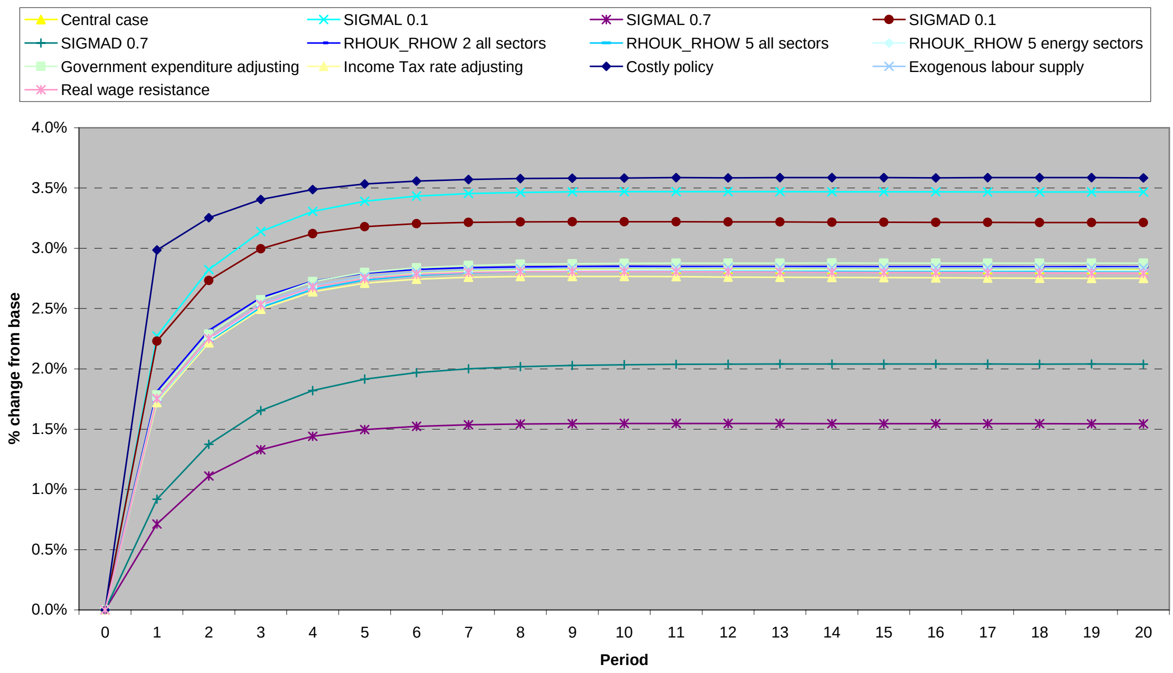


Figure 5.10 Impact on CO2 emissions from fuel use divided by GDP for central case and sensitivity analysis

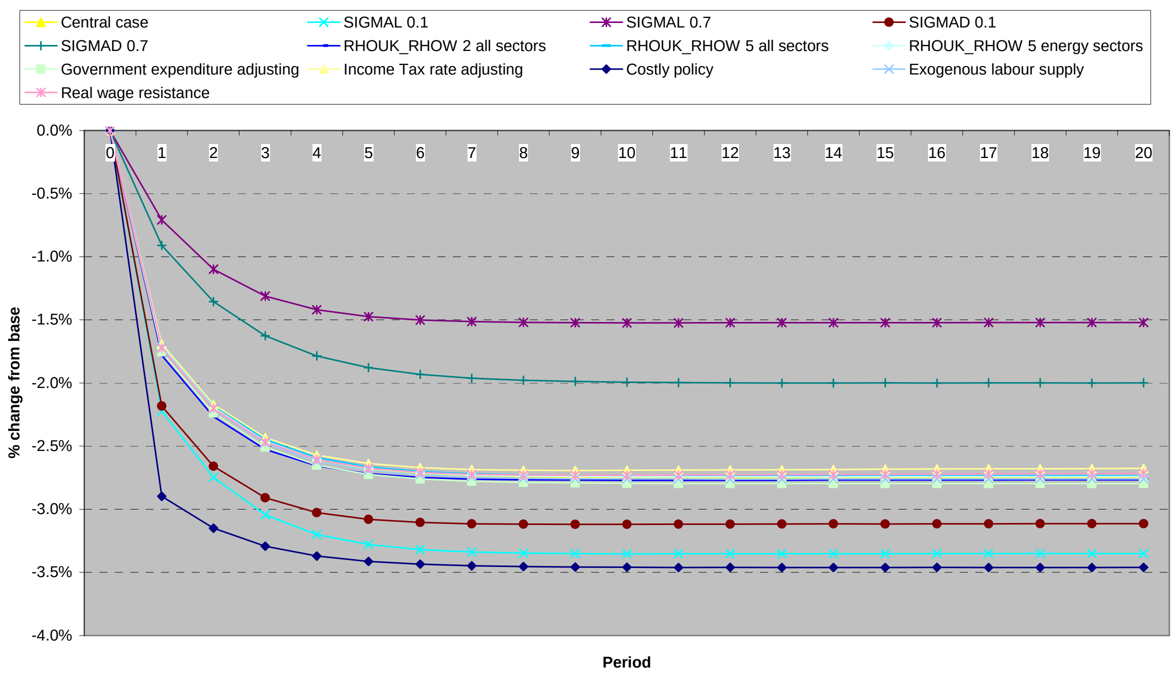


Figure 5.11 Impact on GDP divided by non-electricity energy for central case and sensitivity analysis

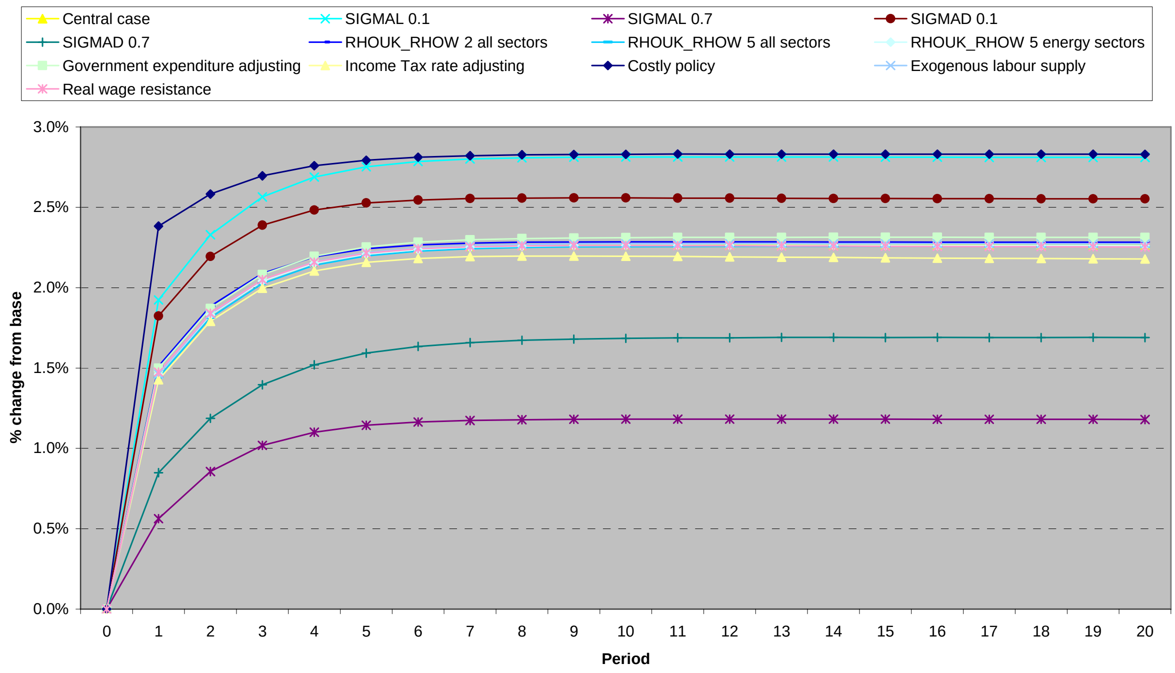
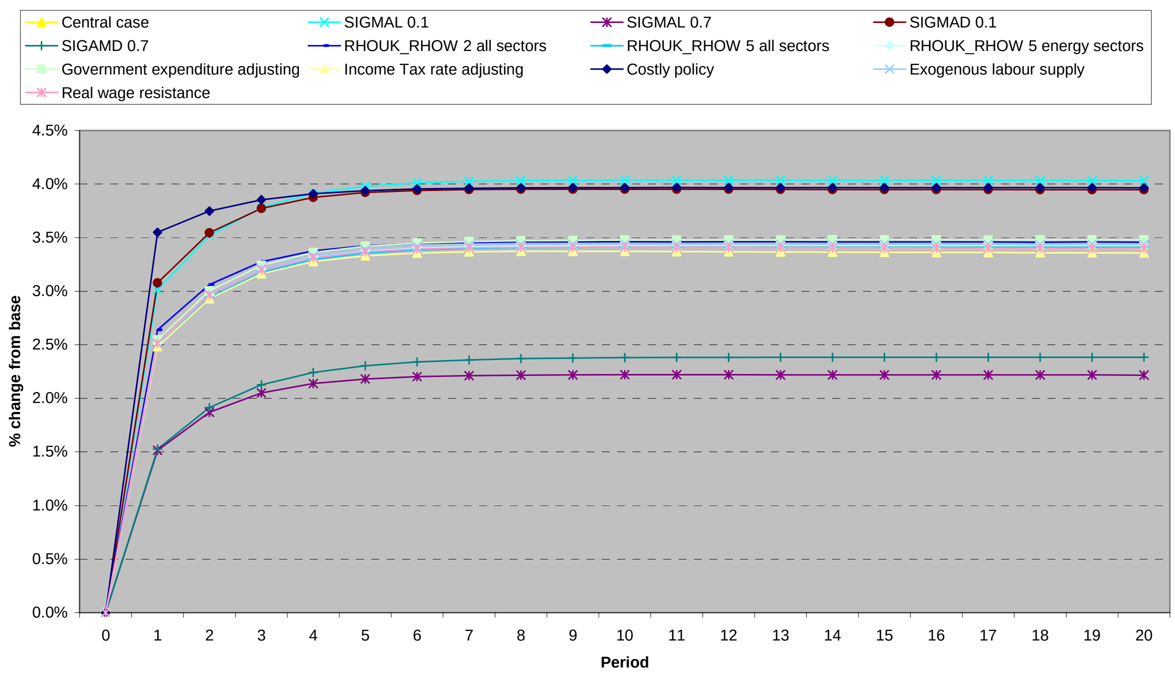


Figure 5.12 Impact on GDP divided by electricity energy for central case and sensitivity analysis



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APPENDIX 1. A CONDENSED VERSION OF UKENVI

Equations	Short run
(1) Gross Output Price	$pq_i = pq_i(pv_i, pm_i)$
(2) Value Added Price	$pv_i = pv_i(w_n, w_{k,i})$
(3) Intermediate Composite Price	$pm_i = pm_i(pq)$
(4) Wage setting	$w_n = w_n\left(\frac{N}{L}, cpi, t_n\right)$
(5) Labour force	$L = \overline{L}$
(6) Consumer price index	$cpi = \sum_i \theta_i \, pq_i + \sum_i \theta_i^{RUK} \, \overline{pq}_i^{RUK} + \sum_i \theta_i^{ROW} \, \overline{pq}_i^{ROW}$
(7) Capital supply	$K_i^s = \overline{K}_i^s$
(8) Capital price index	$kpi = \sum_i \gamma_i \, pq_i + \sum_i \gamma_i^{RUK} \, \overline{pq}_i^{RUK} + \sum_i \gamma_i^{ROW} \, \overline{pq}_i^{ROW}$
(9) Labour demand	$N_i^d = N_i^d(V_i, w_n, w_{k,i})$
(10) Capital demand	$K_i^d = K_i^d(V_i, w_n, w_{k,i})$
(11) Labour market clearing	$N^s = \sum_i N_i^d = N$
(12) Capital market clearing	$K_i^s = K_i^d$
(13) Household income	$Y = \Psi_n N w_n (1 - t_n) + \Psi_k \sum_i w_{k,i}(1 - t_k) + \overline{T}$
(14) Commodity demand	$Q_i = C_i + I_i + G_i + X_i + R_i$

App. 1. (cont.) Equations	Short run
(15) Consumption Demand	$C_i = C_i\left(pq_i, \bar{p}q_i^{RUK}, \bar{p}q_i^{ROW}, Y, cpi\right)$
(16) Investment Demand	$I_i = I_i\left(pq_i, \bar{p}q_i^{RUK}, \bar{p}q_i^{ROW}, \sum_i b_{i,j} I_j^d\right)$ $I_j^d = h_j\left(K_j^d - K_j\right)$
(17) Government Demand	$G_i = \bar{G}_i$
(18) Export Demand	$X_i = X_i\left(p_i, \bar{p}_i^{RUK}, \bar{p}_i^{ROW}, \bar{D}^{RUK}, \bar{D}^{ROW}\right)$
(19) Intermediate Demand	$R_{i,j}^d = R_i^d\left(pq_i, pm_j, M_j\right)$ $R_i^d = \sum_j R_{i,j}^d$
(20) Intermediate Composite Demand	$M_i = M_i\left(pv_i, pm_i, Q_i\right)$
(21) Value Added Demand	$V_i = V_i\left(pv_i, pm_i, Q_i\right)$
(22) Pollutants (output-pollution coefficient)	$POL_k = \sum_i \phi_{i,k} Q_i$
(23) Pollutants (CO_2)	$POL_{CO2} = \sum_i \left[\sum_j (e_{i,f} . f_{i,f}) + (g_i . \kappa_i) + h_i \right] Q_i$
Multi-period model	**Stock up-dating equations**
(24) Labour force	$L_t = L_{t-1} + nmg_{t-1}$
(25) Migration	$\frac{nmg}{L} = nmg\left(\frac{w_n(1-t_n)}{cpi}, \frac{w_n^{RUK}(1-t_n)}{cpi^{RUK}}, u, u^{RUK}\right)$
(26) Capital Stock	$K_{i,t} = (1-d_i)K_{i,t-1} + I_{i,t-1}^d$

NOTATION

Activity-Commodities

i, j are, respectively, the activity and commodity subscripts (There are twenty-five of each in UKENVI: see Appendix 2.)

Transactors

RUK = Rest of the UK, ROW = Rest of World

Functions

pm (.), pq(.), pv(.)	CES cost function
k^S(.), w(.)	Factor supply or wage-setting equations
K^d(.), N^d(.), R^d(.)	CES input demand functions
C(.), I(.), X(.)	Armington consumption, investment and export demand functions, homogenous of degree zero in prices and one in quantities

Variables and parameters

C	consumption
D	exogenous export demand
G	government demand for local goods
I	investment demand for local goods
I^d	investment demand by activity
K^d, K^S, K	capital demand, capital supply and capital employment
L	labour force
M	intermediate composite output
N^d, N^S, N	labour demand, labour supply and labour employment
Q	commodity/activity output
R	intermediate demand
T	nominal transfers from outwith the region
V	value added
X	exports
Y	household nominal income
b_{ij}	elements of capital matrix
cpi, kpi	consumer and capital price indices
d	physical depreciation
h	capital stock adjustment parameter
nmg	net migration

pm	price intermediate composite
pq	vector of commodity prices
pv	price of value added
$\mathbf{t_n}$, $\mathbf{t_k}$	average direct tax on labour and capital income
u	unemployment rate
$\mathbf{W_n}$, $\mathbf{W_k}$	price of labour to the firm, capital rental
Ψ	share of factor income retained in region
θ	consumption weights
γ	capital weights
$\mathbf{POL_k}$	quantity of pollutant k (output-pollution approach)
$\mathbf{POL_{CO2}}$	quantity of CO_2
ϕ_{ik}	output-pollution coefficients
$\mathbf{e_{ij}}$	fuel use emissions factors
$\mathbf{f_{ij}}$	fuel purchases
$\mathbf{g_i}$	import emissions factors
κ_i	import purchases
δ_i	process output-pollution coefficients

APPENDIX 2: DATA SOURCES AND THE UK SAM

For this report, a computable general equilibrium (CGE) model – UKENVI - has been developed and used to simulate a range of alternative energy efficiency improvements. This model relies on an economic dataset parameterised on an appropriately constructed Social Accounting Matrix (SAM) of the UK, which is itself constructed around an Input-Output (IO) table of the UK for 2000. Due to the lack of appropriately constructed official annual IO tables for the UK, this IO table was constructed using data from previously published official UK economic accounts. Part 1 details how an appropriately disaggregated 25-sector IO table for the UK was constructed for the year 2000, while Part 2 explains how this table was augmented with information from a set of Income-Expenditure (IE) accounts to construct the benchmark SAM dataset for UKENVI. Part 3 explains how the environmental input-pollution coefficients were constructed.

Part 1: Construction of Input-Output database for the United Kingdom in 2000

A: Introduction

UKENVI is a flexible modelling framework that can be used to simulate the system-wide effects of different economic shocks. The framework can be used to simulate regional or national economies, and has recently been used for simulation of the economy of Scotland (Hanley *et al*, 2006). The input to UKENVI is an appropriately constructed SAM for the target economy, built around an IO table for a chosen base year. For this case, a SAM was constructed for the UK in 2000, built around an IO table for 2000.

This United Kingdom IO table for 2000 needs to be constructed as an appropriate official IO table has not been published for the UK since 1995. It is believed that UK tables for 2000 will be published towards the end of 2007, however this is too late for this project, making it necessary that IO tables are estimated.

Currently, National Statistics produce annual Supply-Use Tables (SUT) for the UK, however in order to convert these into analytical IO format, extra data are required on commodity taxes, distribution margins and imports at the sectoral level. This would allow production of a Product-by-Industry (PxI) IO table, which can then be converted into a Product-by-Product (PxP) or Industry-by-Industry (IxI) format using a make matrix. However due to confidentiality constraints National Statistics do not make these commodity tax, distribution margin or make matrices public, so the necessary conversions cannot be made to the annually published SUT. The option we have chosen at the current time is to roll the 1995 analytical tables forward to 2000. This method is identical to that used for a previous ESRC-funded project and an existing EPSRC-funded project which required a UK IO table for 1999 and 2000 respectively.

Before the method is outlined, we highlight one major problem with the approach used. The control total data that are suitable for rolling forward the 1995 analytical tables are the column totals of the SUT, which give gross industry output. However, only PxI and PxP tables are available for 1995. We cannot roll forward the PxP tables because the SUT only gives gross output of products in purchaser prices, and do not distinguish between imports and locally produced gods. Therefore, the approach we use is to roll forward the 1995 PxI tables, and then use a mechanical balance program to product an IxI table for the UK in 2000.

The balancing process means that we allow the program to randomly reallocate products to industries, rather than systematically reallocating the off-diagonal elements from the make matrix (of which we have no knowledge). As previously noted, this process is obviously unsatisfactory since we would hope to use an official National Statistics publication. However without analytical tables for the UK economy since 1995, this is a necessary process.

B: Method

As explained above, the method used to estimate a UK IO table for the year 2000 begins with the 1995 Domestic Use table. This 122-sector table is then converted to 2000 prices using a GDP deflator. Coefficients are then calculated from the updated Domestic Use table, which give the purchases made by each sector *i* from other domestic sectors *j*, imports and taxes on products as a proportion of total sectoral *i* output. The published 2000 SUT for the UK is also formatted at this stage to provide consistent sectoral totals for intermediate inputs at purchasers' prices (which include domestic and imported inputs and taxes on products) as well as sectoral totals for taxes on production, compensation of employees and gross operating surplus.

The next step uses the elements gathered above to construct an unbalanced table, which is then balanced using a mechanical balancing procedure. Firstly, the sectoral coefficients for the intermediate inputs from the updated Domestic Use table are applied to the 2000 SUT sectoral totals for intermediate inputs. Then the values for taxes on production, compensation of employees and gross operating surplus are put into the unbalanced table as they appear in the aggregated 2000 SUT. The resulting table is unbalanced as the rows and columns (showing sectoral gross inputs and outputs) aren't equal – which is necessary for an analytical IO table. The column totals sum to gross output from the UK SUT for 2000 by construction, however the rows remain unbalanced at this stage.

At this stage, the unbalanced table is aggregated from 122 sectors to the required level of sectoral aggregation. UKENVI can operate with 25 sectors, including five energy sectors - coal, gas, oil and electricity (renewable and non-renewable). The specific sectoral aggregation for this project was discussed with DEFRA to provide information for a range of sectors of particular interest. The model was initially balanced to 24 sectors however, due to the UK SUT tables not distinguishing between renewable and non-renewable electricity generation. The electricity sector was disaggregated into these two sub-sectors after the IO table was balanced. The sectoral aggregation, with the IOC and SIC codes used, is shown in Table 2A below.

Table 2A: Sectoral aggregation used for UK 2000 IO table

Sector	*SIC (92)*
Agriculture, forestry and fishing	1, 2, 5
Other mining and quarrying, including oil and gas extraction	11 to 14
Mfr - Food and drink	15.1 to 16
Mfr - Textiles	17.1 to 19.3
Mfr - Pulp, paper and articles of paper and board	21.1 to 21.2
Mfr - Glass and glass products, ceramic goods and clay products	26.1 to 26.4
Mfr - Cement, lime plaster and articles in concrete, plaster and cement and other non-metallic products	26.5 to 26.8
Mfr - Iron, steel first processing, and casting	27.1 to 27.5
Mfr - Other metal products	28.1 to 28.7
Mfr - Other machinery	29.1 to 29.7
Mfr - Electrical and electronics	30 to 33
Mfr - Other manufacturing	20, 22, 24.11 to 25.2, 34 to 37
Water	41
Construction	45
Distribution and transport	50 to 63
Communications, finance and business	64.1 to 72 and 74.11 to 74.8
Research and development	73
Public admin and education	75+80
Health and social work	85.1-85.3
Other services	90-95
Coal (Extraction)	10
Oil processing and nuclear refining	23
Gas	40.2 to 40.3
Electricity - renewable	40.1
Electricity - non-renewable	40.1

The final stage of the construction is to create control totals for the new 2000 IO table and to balance the unbalanced table to these totals. Control totals are needed for sectoral gross output/inputs, all elements of final demand (households, government, investment, inventories (stocks) and exports) and primary inputs (imports to the UK, taxes paid on products and production, compensation of employees and gross operating surplus). Control totals for sectoral gross outputs/inputs are taken as sectoral gross output at basic prices from the UK SUT for 2000. Final demand control totals for households (including non-profit institutions serving households), general government, investment (as gross fixed capital formation), inventories and stocks and exports to the rest of the World are taken from the SUT for 2000 figures for total consumption by these groups.

Control totals for primary inputs are then all that is necessary for the balanced UK IO table. Firstly, totals are available from the UK 2000 SUT for compensation of employees, gross operating surplus, net taxes on production and net taxes on products. It is a feature of a balanced IO table that the totals for final demands balance the totals for primary inputs. The remaining control total for imports to the UK are thus constrained by this identity, making this figure the difference between total final demands and total primary inputs without imports.

The last part of the procedure is to apply the RAS balancing technique to the unbalanced table, using all the control totals obtained at the previous stages, and the unbalanced table. As previously stated, this adjusts the entries in the unbalanced table to constrain them to the control totals, and provides a balanced 24-sector IO table for the UK in 2000.

C: Electricity disaggregation

As noted above, the UK IO table was constructed with a single electricity sector. AMOSENVI (Hanley *et al*, 2006) used experimental data for 1999 from the Scottish Executive to disaggregate this single row and column in the IO accounts for Scotland into five electricity generation technologies – nuclear, coal, gas, hydro and wind. This data was used in the absence of official data on the different purchases of different electricity generation technologies, however the data were adjusted to reflect the differences in the pattern of electricity generation in the UK compared to Scotland.

Thus, the single UK electricity sector was disaggregated into five electricity generation sectors based on the experimental data for generation facilities in Scotland, before being aggregated to renewable and non-renewable for the UKENVI model. The final composition of the UK electricity sector (between renewables and non-renewables) will differ from that of the UK, reflecting the larger share of electricity generated in Scotland from renewable technologies (around 10 per cent compared to 3.5 per cent), the greater use of nuclear generation technology in Scotland, and the correspondingly smaller share of gas for electricity generation than in the UK as a whole.

Part 2: UK Income and Expenditure (IE) accounts for 2000

A set of income-expenditure accounts for the United Kingdom in 2000 was constructed to meet all the additional data requirements for construction of a Social Accounting Matrix (SAM). Hence, each entry necessary for extending the UK 2000 Input-Output (IO) table into a SAM would come from within these income and expenditure accounts. Completion of a set of internally consistent income-expenditure accounts means that the SAM will therefore automatically balance. Balancing is constrained by the fixed IO entries and it is therefore necessary to manually balance the SAM on the basis of the additional entries in the income-expenditure accounts alone.

On of the key characteristics of a SAM is that it is an example of single-entry bookkeeping, in that any item of expenditure in one account (a column entry) must appear as an item of income in another (a row entry). By constructing five sets of income-expenditure accounts – covering households, corporations, government, capital and the external sector – observing this rule, it is possible to fulfil all the additional data requirements and create a balance SAM.

In constructing the income-expenditure accounts we begin with the three local transactors – households, corporations and government – for which data are more readily available from existing published sources. Figure 1 shows the outline of the format used for these three accounts.

Figure 1: Template used to construct income-expenditure accounts for the three local transactors (households, corporations and government)

Income	*Expenditure*
Income from employment (Households only)*	IO final demand expenditure (including expenditure taxes)*
Net commodity taxes (Government only)*	

Income from other value added (OVA)*

Payments from corporations**	Payments to corporations**
Payments from government**	Payments to government**
Payments from households**	Payments to households**
Transfers from ROW***	Transfers to ROW***
	Payments to capital (savings)***

Notes:

1. Items marked with * are fixed by the balanced IO table (using a share parameter in the case of income from OVA
2. Items marked with ** are constrained by the corresponding entry in another account – e.g. payments to corporations in the household account must correspond to payments from households in the corporations account.
3. Items marked *** are entries which ensure that income equals expenditure, and thus balance the income-expenditure account.

The Household Account

Information necessary to complete the household accounts included income from employment and total expenditure (both of which were taken from the UK IO table). Additional information required for this account, including total household income and household share of other value added (OVA), came from the UK Blue Book (ONS, 2004). Payments from corporations was the sum of three elements - total dividend payments by UK companies going to UK households, estimated using Hill and Taylor (2001), income generated from private pensions and other mixed income (both from the Blue Book).

Total payments from government were again the sum of three elements – social security payments (taken from the UK Blue Book), dividends from public corporations to UK households (based on data from Hill and Taylor, 2001) and net other mixed income. Total household income for 2000 in the UK was known, and so payments to the external sector were used as the balancing item in the household income account.

Total household expenditure was the sum of payments to corporations, government, external sector and savings (payments to capital). The payment to corporations' element was the balancing item in this account, given the difficulty in estimating this figure. Payments to government are estimated from a number of taxes; specifically income and capital gains tax, inheritance tax, stamp duties, insurance premium tax, council tax and social security contributions. For each of these taxes we obtain values for the total government receipts in each financial year 1999-2000 and 2000-2001 and annualise these figures to produce a value for 2000, using one quarter of the 1999-2000 figure and three-quarters of the 2000-2001 figure.

In order to estimate UK household payments to the rest of the world it was required to estimate the portion of wage and non-wage income transferred. The final element in the household expenditure account, households savings (or payments to capital) is estimated by taking the ratio of household saving to income (5.54%) from the UK 2004 Blue Book (gross saving as a portion of total resources) and applying this ratio to the control figure for total household income.

The Government Account

The entries in the UK government income-expenditure accounts that can be drawn directly from the UK Input-Output table for 2000 are final demand expenditure and net commodity tax income. Total government expenditure in the UK can also be obtained, but not directly from the UK IO tables for 2000. It can be estimated as the annualised (as per above) figure for Total Government Expenditure from PESA (2002/3) (HM Treasury, 2004). Also, the value for government income from Other Value

Added (OVA) are estimated as the value for Other Value Added from the Public administration and defence sectors within the UK IO table for 2000.

The other entries in the government income account were payments from households (which was taken as the households payments to government figure) and payments from corporations (which was the balancing item in the government income account).

The other entries in the government expenditure account were payments to households (taken from the household income account), payments to the external sector (equal to the amount of net subsidies paid by the UK government to the rest of the world (UK Blue Book, 2004)), payments to capital (calculated from the investment data required for the CGE model) and payments to corporations (which was the balancing item in this account).

The Corporate Account

The IO items "income from employment" and "IO expenditure" are not relevant in the corporate account of the income-expenditure accounts as these are already taken account of within the borders of the input-output table, with sectoral information on both these values.

Income (OVA) in the corporate account is equal to total OVA (from the IO table) minus OVA in the government and household income accounts. Payments from corporation to other corporations will be, by definition, equal to zero in an aggregate account. All outlays for one corporation in the UK will be offset in the income-expenditure accounts by a symmetrical entry for another corporation in the UK.

Payments to corporations from government and households were obtained from the earlier income expenditure accounts, while payments from the external sector were also estimated. On the expenditure side, payments to government, household and the external sector were taken from previous balanced accounts. Payments to capital (savings) were equivalent to receipts from corporations in the capital income account calculated below.

The External Account

Income from the sale of goods and services in the UK by the external transactor (the rest of the world) is given the import row of the UK IO table for 2000. Similarly, the export expenditure column in the IO table gives expenditure on UK goods and services by the external transactor. The additional items to account for in the SAM are transfers of income in both directions – i.e. between firms operating in the UK, local households and government, and the external transactor. However, these are all accounted for in the government, corporation and household accounts detailed above.

The Capital Account

Receipts to the capital account consist of savings from the household, corporations, government and external accounts. Capital expenditures are gross fixed capital formation and stock building, which are determined in the IO table for the UK in 2000. The extra information required for the income part of this account come from the payments to capital values in the expenditure sections of the household and government accounts. The income from corporations figure is used as the balancing item in this account.

Investment demands

The IO table and SAM contain information on which portion of each sectors outputs are used for the purposes of capital formation. However, they do not tell us in which sectors the demand for this capital formation comes from. For example, if a bank decides to invest in a new building and contracts a local construction firm to build it, this will enter the IO accounts as a final demand for construction output in the Gross Domestic Fixed Capital Formation column of the IO table. In other words, what is provided is information on the supply of capital formation. For CGE modelling, the supply of capital formation in the UK economy is also required.

The distribution of investment across the production sectors of the economy is another variable required for the base year data set of the CGE model, to allow the estimate of capital stocks. Therefore, it is assumed that investment is equal to long-run depreciation in the base year (where all markets are taken to be in long-run equilibrium). Thus, the base year capital stock in each sector is estimated by grossing up investment demands using the depreciation rate for capital – i.e. dividing each sectors investment demand by the depreciation rate, which is assumed, in the absence of econometric estimates, to be equal to 0.15 in each sector.

Labour supply data

In a SAM worksheet the (full-time equivalent, FTE) labour employed by each of the 25 UK production sectors is reported in the base year, 2000. The FTE sectoral employment figures for 2000 in the UK are calculated from the Annual Business Inquiry (ABI) for Great Britain for 2000, plus employment data at the same sectoral aggregation in Northern Ireland from the Northern Ireland Annual Business Inquiry (NIABI). Part-time workers were assumed to be equal to 0.3 of full-time workers.

Part 3: Construction of the UK input-pollution coefficients for the UKENVI model

There are four types of changes in economic activity that will affect the level of atmospheric emissions resulting from that economic activity. Scale and compositional effects relate to the size of a region, and the sectors that make up the economic activity of that region. As the scale of a region changes there would be expected to be a resulting impact on emissions from that increased activity. Similarly, as the economic composition of industry within a region changes, it would be expected that the level of emissions would alter. A third type of change will occur from changes in production technology, as the relationship between economic output and emissions changes, however modelling this element is beyond the scope of UKENVI model.

The fourth type of change is that coming from changes in fuel input use, and it is this change that is modelled in UKENVI. All sectoral pollution is linked to sectoral uses of fuel in the form of coal, oil and gas, and so as UKENVI predicts changes in the sectoral demand for each fuel type, the impact of these changes on emissions can be estimated.

The common way to model economic-environmental linkages is through the use of output-pollution coefficients. This uses the base year relationship between output and emissions, and can be used to relate changes in sectoral output to changes in emission by each sector. This was used in AMOSENVI to account for the production of sectors that were inherently emitting, irrespective of production technology used. With UKENVI however, the focus is solely on changes in energy use related CO_2 emissions, i.e. changes in emissions due to changes in energy use. As such, the changes in total emissions may be different because as activity levels change, non-fuel combustion process emissions may change.

For each sector, input-pollution coefficients were estimated using data on each sector's use of oil, coal and gas fuels in 2000 (from ONS data) and physical emissions factors for the UK from 1999, linking emissions by fuel to use of that fuel in each of the 25 sectors of UKENVI. It was necessary to use physical emissions factors for 1999, as more recently published data were not available.

Endnotes

[1] In fact Pearce (2001) includes a fourth motivation, but it applies to improvements in the efficiency of households' direct energy use, which we do not consider in this paper.

[3] UKENVI is a UK CGE with an appropriate sectoral disaggregation and set of linked pollution coefficients, developed specifically to allow us to investigate environmental impacts.

[4] Parameter α is calibrated so as to replicate the base period (as is β in equation [5]). These calibrated parameters play no part in determining the sensitivity of the endogenous variables to exogenous disturbances but the initial assumption of equilibrium is an important assumption,

[5] Our treatment is wholly consistent with sectoral investment being determined by the relationship between the capital rental rate and the user cost of capital. The capital rental rate is the rental that would have to be paid in a competitive market for the (sector specific) physical capital: the user cost is the total cost to the firm of employing a unit of capital. Given that we take the interest, capital depreciation and tax rates to be exogenous, the capital price index is the only endogenous component of the user cost. If the rental rate exceeds the user cost, desired capital stock is greater than the actual capital stock and there is therefore an incentive to increase capital stock. The resultant capital accumulation puts downward pressure on rental rates and so tends to restore equilibrium. In the long-run, the capital rental rate equals the user cost in each sector, and the risk-adjusted rate of return is equalised between sectors.

[6] Note that this treatment of pollution generation from imports implies the assumption that the *composition* of imports from RUK and ROW is fixed.

[7] Indicator 1 in Scottish Executive (200a, 2003)

[8] Indicators 12 and 13 in Scottish Executive (2002a, 2003)