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Do increases in resource productivity improve environmental quality and sustainability?

by

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Abstract

Resource Productivity is increasingly seen as an important aspect of sustainability by governments world-wide. Making more with less seems to be intuitive in terms of reducing the burden on the environment while allowing for economic development. In the UK policy context there appears to be an acceptance that enhanced resource productivity is “good for the environment”. However, there is a debate in the literature concerning the possibility that any beneficial impact on the environment may be partially (“rebound”) or even more than wholly (“backfire”) offset. This paper clarifies the theoretical conditions under which such effects would occur and explores their likely significance using a computable general equilibrium (CGE) model of the Scottish economy. We find that an improvement in energy efficiency ultimately *increases* energy use and results in a worsening of the GDP to CO2 emissions ratio. The time interval of analysis proves significant, with rebound effects eventually growing into backfire. The reason is simple: energy efficiency improvements result in an effective cut in energy prices, which produces output and substitution effects that stimulate energy demands. However, the presence of backfire effects does not imply irrelevance of efficiency-enhancing policies: rather it implies that such policies alone are insufficient to improve the environment. The implication is that energy policies need to be co-ordinated.

JEL Classification Q01, Q40, Q43

Keywords: backfire; CGE models; energy efficiency; rebound; resource productivity; sustainability indicators.

1. Introduction and background

In this paper we build on the literature on “rebound” and “backfire” effects (Khazzoom 1980, Brookes 1990, Birol and Keppler, 2000; Herring, 1999; Saunders, 2000) to explore the conditions under which the notion that energy efficiency results in rebound or backfire would be expected to hold theoretically, and present some empirical evidence from a regional, energy-economy-environment computable general equilibrium (CGE) model.

We also aim to inform the policy debate in the UK , where sustainable development is a key objective of UK government policies at the national and regional levels (Department of Environment, 1996). 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 associated with a given level of economic activity. This issue is also receiving increasing emphasis in a regional development context with, for example, the Scottish Parliament recently reaffirming its commitment to sustainable development (Scottish Executive, 2002, 2003, 2005). The success of national sustainability programmes will depend upon policy delivered at the regional level; the region therefore appears to be a very relevant level on which to focus policy evaluation.

In Section 2 we explain what is meant by rebound and backfire effects in responses to changes in resource productivity, summarise previous results and sketch our own analysis of the likely system-wide ramifications, in terms of possible rebound and backfire effects, of a stimulus to energy efficiency. In Section 3 we provide a general introduction to our CGE model of Scotland, AMOSENVI. In Section 4 we present the results of simulating an across the board stimulus to resource productivity, and provide sensitivity analysis around these central results. We conclude in Section 5.

2. Resource productivity enhancements, rebound and backfire

Theoretical Considerations

Formal analyses of rebound and backfire effects have tended to analyse the impact of an energy efficiency stimulus in the form of an energy-saving technical change in the production function. Modern theory has helped to identify the conditions that are likely to facilitate significant rebound and even backfire. Saunders' (1992, 2000a,b, 2006) analyses of rebound and backfire effects provide probably the best known, and most formal, analyses of the issues from an explicitly macroeconomic perspective. While these analyses add significantly to our understanding of the long-run macroeconomic impacts of energy efficiency changes, the context in which Saunders' chooses to analyse their impact, namely an aggregate neoclassical growth model of a closed economy and later neoclassical production theory, is rather restrictive. The consequence is that, despite being regarded as one its leading advocates, Saunders (e.g. 2000a,b) inadvertently tends to understate the case for macroeconomic rebound and backfire effects. In particular, his analysis 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, as we now discuss.

Consider the system-wide impact of enhanced *energy* efficiency within a one good macroeconomic model initially. This is represented by imposing energy-augmenting technical progress within the aggregate production function. Let us identify energy in natural units (this could be any physical measure of energy, e.g. kWh, BTU or PJ) as E, a productive/efficiency unit of energy as ε, and the change in energy augmenting technical progress (affecting the level of output produced per unit of physical energy input) as ρ, then:

(1) $$\varepsilon = (1+\rho)\mathrm{E}$$

A productive unit of energy, ε, is most simply defined in terms of output produced. For example, suppose $\varepsilon=10$ units of output. Assume we start with no technological progress, so that $\varepsilon=\mathrm{E}$. If we have a 50% increase in energy productivity, so that $\rho=0.5$, then from (1) $\varepsilon=15$, i.e. one productive unit of energy will produce 15 units of output. The subsequent price of energy, measured in productive/efficiency units, p_ε, is given by:

(2) $$p_\varepsilon = \frac{p_E}{1+\rho} < p_E$$

where p_E is the price of energy in natural units.

With constant energy prices in natural units, an improvement in energy efficiency reduces the price of energy in terms of productive units, i.e. the amount of output that can be produced per unit of physical energy. Taking our simple numerical example above, if the price of physical energy required to produce one unit of output prior to the technological improvement is £3 (where $p_E=p_\varepsilon$), if we have an improvement such that $\rho=0.5$, the same amount of physical energy measured in productive units will produce more 50% more output, so that the *effective* price of energy input per unit of output falls to £2 ($p_\varepsilon=£2$)

Measured in natural units, with physical energy prices constant, whether an improvement in energy efficiency reduces physical energy use depends on the general equilibrium own-price elasticity of demand for energy in productive/efficiency units.[1] Ex post, this corresponds to the responsiveness of total physical energy consumption in the economy to the improvement in energy efficiency, denoted in [3] by η_ρ:

[3] $$\eta_\rho = \frac{\Delta E / E}{\alpha\rho}$$

Where α is the proportion of total energy use directly impacted by the improvement in energy augmenting technological progress. If η_ρ is negative but less than unity (i.e. the change in total energy use is negative but less than proportionate to the increase in energy efficiency, ρ), we have an economy-wide rebound effect, defined as:

[4] $$R = 1 + \eta_\rho$$

Where η_ρ is -1, rebound is zero since energy demands fall in proportion to the stimulus to efficiency. Where η_ρ is positive, R is greater than unity, the fall in the price of a productive unit of energy, p_ε, generates an increase in expenditure on energy so that overall energy use in physical units rises: substitution, income and output effects would dominate efficiency effects, and we have an economy-wide backfire effect. This conceptual approach is ideal for a fuel that is imported, where the natural price is exogenous, or only changes in line with the demand measured in natural units.

However, in an empirical context there are two problems that introduce more complexity. The first is that energy is often a domestically produced product that uses energy as one of its inputs. This means that the price of energy in physical units will be endogenous, giving further impetus for rebound effects. The second is the identification of the general equilibrium elasticity of demand for energy. The responsiveness of energy demand at the aggregate level to changes in (effective and actual) prices will depend on a number of parameters and characteristics in the economy. As well as elasticities of substitution in production, which tend to receive most attention in the literature (see Sorrell et al, 2007, for an excellent review) these include: price elasticities of demand for individual commodities; the degree of openness/extend of trade (particularly where energy itself is traded, as in the case of Scotland); the elasticity of supply of other inputs/factor (as this affects the ability of energy users to energy for other commodities, and will vary systematically over the time period in question); the energy intensity of different activities; and income elasticities of energy demand (the responsiveness of energy demand to changes in household incomes).

In our empirical analysis we explore the sensitivity of rebound and backfire effects to the values of key parameters and thereby reveal important information about the determinants of the importance of these effects.However, before proceeding to our own empirical analysis, we consider existing evidence on rebound and backfire effects.

Empirical evidence of rebound and backfire

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. However, 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), which suggests that the rebound effect is typically low-to-moderate in scale. However, these studies tend to be microeconomic in nature with a short-term focus, characteristics that our analysis suggests are likely to bias downwards estimates of the scale of rebound effects. Bentzen (2004) considers the direct rebound effect of improvements in energy efficiency in particular U.S. manufacturing sectors using a dynamic ordinary least squares approach. Aggregate time series data are used to generate translog production functions, 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. This is not directly comparable to a direct rebound effect; however, 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.[2] 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.

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. 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.

As argued above, a system-wide perspective on the modelling the impacts of an improvement in resource productivity may lead to bigger rebound and backfire effects being found. For example, Glomsrød and Taoyuan (2005) use CGE analysis to look at the effect of energy efficiency improvements in China, and note (p.535) that …"the attractive energy efficiency gains stimulate 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". On the other hand, Grepperud's and Rasmussen's (2004) evidence from a CGE of Norway is not supportive of the presence of widespread significant rebound effects (with the exception of manufacturing), although the fact that they explore sectoral-specific, rather than system-wide, efficiency changes may be significant here, since this limits the scale of the general equilibrium effects.

3. AMOSENVI: An energy-economy-environment CGE model of Scotland.

CGE models are now being extensively used in studies of the economy-environment nexus, though typically at the level of the national economy (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.) There are, however, a limited number of regional applications of CGEs to environmental issues, including 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. CGE models are particularly suited to studying the rebound and backfire effects of energy efficiency improvements (the resource productivity shock used here), since they allow the system-wide effects of such a shock to be captured. To revise, these comprise (i) a need to use less physical energy inputs since to produce any given level of output (the pure engineering effect); (ii) an incentive to use more energy inputs since their effective price has fallen; (iii) a compositional effect in output choice, since more energy-intensive products benefit relatively more from this fall in the effective price; (iv) an output effect, since supply prices fall and competitiveness increases; and (v) an income effect as household incomes rise.

Here we employ AMOSENVI, a CGE modelling framework parameterised on data from a UK region, Scotland.[3] We next provide a brief description of the general model framework. A more formal description is given in Appendix 1.

General structure

AMOSENVI has 3 transactor groups, namely households, corporations, and government[4]; 25 commodities and activities, 5 of which are energy commodities/supply (see Figure 1 and Appendix 2 for details); and two exogenous external transactors (the Rest of the UK (RUK) and the Rest of the World (ROW)). Throughout this paper commodity markets are taken to be competitive. We do not explicitly model financial flows, our assumption being that Scotland is a price-taker in competitive UK financial markets.

The AMOSENVI 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. The external regions, RUK and ROW are exogenous but export demand for Scottish outputs and Scottish import demands are sensitive to changes in relative prices between (endogenous) Scottish and (exogenous) external prices (Armington, 1969). Investment is a little more complex as we discuss below.

We generally impose a single Scottish labour market characterised by perfect sectoral mobility. We also assume that wages are subject to a regional bargained real wage function in which the regional real consumption (take-home/post tax) wage is directly related to workers' bargaining power, and therefore inversely to the regional unemployment rate (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 regional econometric work reported by Layard *et al* (1991):

$$[5] \qquad w_{s,t} = \alpha - 0.068u_s + 0.40w_{s,t-1}$$

where: w_s and u_s are the natural logarithms of the Scottish real consumption wage and the unemployment rate respectively, t is the time subscript and α is a calibrated parameter.[5] Empirical support for this "wage curve" specification is now widespread, even in a regional context (Blanchflower and Oswald, 1994).

Within each period of the multi-period simulations using AMOSENVI, 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. 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.[6]

Where migration is incorporated in the model, population is also updated "between" periods. We take net migration to be positively related to the real wage differential and negatively related to the unemployment rate differential in accordance with the econometrically estimated model reported in Layard *et al* (1991). This model is based on that in Harris and Todaro (1970), and is commonly employed in studies of US migration (e.g. Greenwood *et al*, 1991; Treyz *et al*, 1993). The migration function we adopt is therefore of the form:

$$[6] \qquad m = \beta - 0.08\left(u_s - u_r\right) + 0.06\left(w_s - w_r\right)$$

where: m is the net in-migration rate (as a proportion of the indigenous population); w_r and u_r are the natural logarithms of the real consumption wage and unemployment rates, respectively, in the rest-of-the-UK, and β is a calibrated parameter. In the multiperiod simulations reported below the net migration flows in any period are used to update population at the beginning of the next period, in a manner analogous to the updating of the capital stocks. The regional economy is initially assumed to have zero net migration, and ultimately, net migration flows re-establish this population equilibrium.

Treatment of energy inputs to production in AMOSENVI

Figure 1 summarises the production structure of AMOSENVI. 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).[7]

Insert Figure 1

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 4 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.

Modelling pollution generation in AMOSENVI

There are several ways to model pollution generation in a CGE framework (see Beghin *et al*, 1995, and Turner, 2002). Here, we relate emissions of CO2 to the use of polluting inputs in the form of the different types of fuel use at different levels of the energy composite (locally-supplied energy inputs) in Figure 1. Scottish CO2 emissions from the combustion in Scotland of imported energy inputs are captured through the use of fixed input-pollution coefficients at the higher nests where the RUK and ROW composite commodities are determined.[8] Both these and the input-pollution coefficients attached to locally supplied energy inputs are determined using data on the CO2 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 CO2 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 CO2 emissions (see Turner, 2002, for a review).

However, modelling input-pollution relationships becomes more complex when it comes to non-CO2 emissions. This is because non-CO2 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 any other pollutants. We also include an output-pollution component for the generation of CO2 emissions (equation 22 in Appendix 1) in addition to the input-pollution links. This reflects the argument of Beauséjour *et al* (1994, 1995) that there is a role for modelling both input-pollution relationships, *and* output-pollution relationships where emissions not only result from input use but also from processes that are inherently polluting. Beauséjour *et al* (1994, 1995) point to processes such as non-ferrous smelting, which generates SO_X, and pulp and paper production, which generates CO2. Here, in the case of CO2 emissions, we identify industrial process emissions relating to the production of mineral products and metal in the 'Mfr metal and non-metal goods' sector (see Appendix 2). We also apply output-pollution coefficients to capture CO2 emissions that occur during extraction activities in the 'Oil and gas extraction' sector and flaring in the 'Refining and distribution of oil' sector. While these are obviously related to energy supply, they are not easily related to energy input use through the application of emissions factors.

Perhaps the single most important feature of the Scottish electricity market for our exercise is the trade in electricity between Scotland and the rest of the UK. Scotland is a net exporter of electricity to the rest of the UK (imports of electricity to Scotland from RUK correspond to just under 10% of Scottish exports of electricity to ROW), which may be beneficial in terms of UK and global sustainability concerns if Scotland is capable of producing electricity using less polluting technology. In our base year of 1999 around 12% of Scottish electricity production was from renewable sources, mainly (around 85%) from hydro technology, in contrast to the UK where only around 3% was generated from renewable sources. However, this trade does have implications in terms of Scotland's ability and responsibility for reducing emissions levels[9], a fact that becomes very apparent in the analysis presented in this study.

Database

The sectoral breakdown of the 1999 social accounting matrix separately identifies sectors of central importance in assessing the likely impact of energy efficiency, so we distinguish among four broad energy types: coal, oil, gas and electricity. We have drawn on experimental data for 1999 supplied by the Input-Output team at the Scottish Executive that disaggregates the electricity sector into the 'Renewable (hydro and wind)' and 'Non-renewable (coal, nuclear and gas)' sectors (see

Figure 1 and Appendix 2). However, the database is still limited in that the electricity sector is reported as a vertically integrated sector in the Scottish input-output accounts, including generation, distribution and supply activities (classed as IOC 85, mapping to activity 40.1 in the Standard Industrial Classification, SIC). When the sector is disaggregated by generation type to identify the 'Renewable' and 'Non-Renewable' sectors, these are also vertically integrated. This is a problem caused by the classification of all electricity production and distribution activities under a single category of activity in the SIC system used to construct the Scottish (and UK) input-output accounts.[10]

While no appropriate data on sectoral emissions and physical fuel use are available for Scotland, it has been possible to introduce some region-specificity to the environmental (CO2 and fuel use) database for Scotland by using the I-O data on the sectoral destination of outputs from the local energy supply sectors. In terms of imported fuels, we have drawn on experimental data provided by the Input-Output team at the Scottish Executive that break sectoral imports down by commodities. A more detailed account is given in Turner (2003), but basically we have taken the following steps to derive the input-pollution coefficients for both locally supplied and imported fuels. First we used UK data on physical fuel intensities for the broad (directly polluting) fuel types – oil, gas and coal – to estimate total Scottish fuel uses. These are then distributed across the production and final consumption sectors identified in the model according to the distribution of local and imported purchases of these fuels implied by the Scottish I-O tables and the experimental data on commodity imports to estimate sectoral fuel uses. UK data on the level of emissions (tonnes) per unit of each fuel type (tonnes of oil equivalent) are then used to derive estimates of direct CO2 emissions resulting from each production and final consumption sector's use of local and imported coal, gas and oil. Finally, we divide each sector's estimated emissions from each type of fuel use by the I-O and (experimental) import-by-commodity data on fuel *purchases* to derive the input-pollution coefficients for both local and imported inputs for the model (tonnes of CO2 per £1million expenditure on each local and imported fuel respectively). See equation 22 in Appendix 1.

To generate the output-pollution coefficients for non-fuel-combustion emissions of CO2 in the 'Mfr metal and non-metal goods', 'Oil and gas extraction' and 'Refining and distribution of oil' sectors, we have used estimates of CO2 emissions in 1999 from the relevant sources reported by Salway *et al* (2001). These are simply divided by the base year outputs for each of these sectors.

Rebound, backfire and sustainability indicators in AMOSENVI

The indicators we incorporate within AMOSENVI reflect those currently or recently advocated as useful by both the UK and Scottish governments. The focus of rebound and backfire effects is clearly the impact of energy efficiency stimuli on the total use of energy: if this falls (proportionately) by less than the increase in efficiency there is rebound; if it actually increases there is backfire. In line with indicators employed by the Scottish Executive (2002a, 2003) focussing on the sustainability of energy consumption and production[11] we identify:

- Energy consumption – total use of electricity in Scotland (gigawatt hours)
- Share of electricity generated using renewable sources (share of total electricity output, in gigawatt hours, from the renewable source sectors)[12]
- Energy consumption – total use of non-electricity energy

The broad target for the first, and most important, of these in the present context is that the consumption of electricity, particularly from non-renewable sources, should decline. Of course, this will happen in response to an energy efficiency enhancement provided that there is no backfire. The direction of change of the indicator is insufficient in itself to indicate the extent of rebound (backfire): but we can infer this by comparing the scale of any reduction (increase) in energy consumption with the scale of the efficiency stimulus. With regard to the share of electricity generated from renewables, there is a specific target that the percentage of electricity generated using renewable sources should increase to 18% by 2010, with a more demanding target to be determined for 2020. We also report results for consumption of non-electricity energy.

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

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

We report these sustainability indicators in our results. Of course, we expect Y to increase in response to the stimulus to energy efficiency, given the effective reduction in the relative price of energy. However, it should be noted that there is no very straightforward relationship between these "relative" indicators of sustainability and the presence of rebound or backfire. In particular, Y/E will only move "perversely" if the extent of backfire is such that the percentage increase in energy use actually exceeds the percentage increase in output. Otherwise Y/E would be expected to increase in response to an energy efficiency stimulus, despite the presence of significant rebound and even backfire, provided the latter is not sufficiently strong to cause E to increase proportionately by more than Y. Not surprisingly, this suggests caution in the use of relative rather than absolute indicators of sustainability in circumstances where the *levels* of energy use (and pollutants) are important, as they clearly are in relation to rebound and backfire, and achievement of Kyoto targets. It seems odd that an improvement in energy efficiency that generated backfire effects could conceivably result in an improvement in sustainability in terms of the output per unit of energy input indicator.

The UK government also tracks the "carbon intensity" of the UK economy, defined as the ratio of output or income (Y) per unit of CO2 emissions (P). Again, a rise in this ratio is interpreted as an improvement in the sustainability of economic development (however, note that, while the energy consumption indicators relate to energy use in Scotland, this CO2 indicator relates to emissions that may result from electricity generation for export). The indicator is defined as:

- Y/P – GDP (£) per tonne of CO2 emissions

The limitations of this relative indicator of sustainability are similar to those based on output per unit of energy input: it would classify rebound and possibly even backfire as improving sustainability as long as output is stimulated by more than CO2 emissions. Yet quite clearly, the change effectively makes it more, not less, difficult to reach Kyoto targets. Again, this serves as a warning to exercise caution in the interpretation of movements in relative indicators of sustainability in circumstances where some sustainability constraints may be binding in absolute terms.

4. Simulation Results

In this Section we present the results of a simulation a 5% increase in energy efficiency in all production sectors. This shock is a one-off step change in technical efficiency, imposed as an energy-augmenting change to the energy composite (see Figure 1). All results are reported in terms of the percentage change from the base year values given by the 1999 Scottish SAM. The economy is taken to be in long-run equilibrium prior to the energy efficiency improvement, so that when the model is run forward in the absence of any disturbance it simply replicates the initial equilibrium each period. All of the reported results refer to percentage changes in the endogenous variables relative to this unchanging equilibrium. All of the effects reported are directly attributable, therefore, to the stimulus to energy efficiency.

Central case scenario

The stimulus to energy efficiency is a beneficial supply-side shock that we would expect to lower prices, improve competitiveness and stimulate output. The broad-brush macroeconomic properties of the simulation(s) are as we would expect. Summary results for aggregate economic indicators for short (fixed population and capital stocks), medium (population re-equilibrated through migration) and long-run (population and capital stocks fully adjusted) equilibria are shown in Table 1. Given the regional bargaining closure we would expect a stimulus to employment, a fall in unemployment and a rise in the real wage, accompanied by a stimulus to exports in the short-run. The net effect on imports depends on the strength of the relative price effect (as Scottish prices fall, imports to production and final consumption activities will fall in favour of locally produced goods) and the stimulus generated by increased economic activity (which will stimulate Scottish demand for all local and imported commodities). In Table 1 the latter effect dominates and imports rise (though by a much smaller amount than exports). In principle, the ability to substitute in favour of the intermediate composite (which includes energy inputs) and away from value-added (labour and capital inputs) at the top level of the production hierarchy in each industry could frustrate the expected labour market effects, but the substitution possibilities are limited and in practice are dominated by the output effect. In-migration ensures that real wages and unemployment return to their original levels over the medium-run and in the long-run capital stocks adjust further enhancing the impacts on output and employment. In the long-run all prices fall in response to the energy efficiency stimulus (given that the real wage is tied down by migration).

A striking feature of these results is the reported strength of rebound effects. In the short and medium runs total electricity and other energy consumption do fall, but only by just over 1% in the face of the 5% stimulus to energy efficiency, implying large rebound effects of over 63% and 68% respectively. In the long-run energy demands actually increase, so that backfire is present (a rebound effect of 131.5% in electricity and 123.5% in other energy consumption). While energy efficiency does initially lower the demand for energy, the increase in competitiveness is concentrated in, and therefore stimulates, the most energy-intensive sectors of the economy. The view that improvements in energy efficiency will reduce energy demand is implicitly predicated upon a view that the general equilibrium demand for energy is price-inelastic. This is unlikely to be the case where energy efficiency changes occur in a small open economy such as Scotland, where the outputs of energy supply sectors are extensively traded.

Insert Table 1

The changes in the outputs of major sectoral groups over the short, medium and long run are shown in Figure 2. The increase in efficiency and consequent positive competitiveness effects lead to positive output effects in most sectors, although the stimulus to the real wage has a countervailing influence in the short run. In the case of some of the energy supply sectors, however, there are also negative output effects due to the fall in intermediate demand as energy productivity increases, combined with the real wage increase.

Insert Figure 2

Figure 2 shows that output in the electricity sectors rises even in the short-run. This is because in the case of the electricity sectors the positive substitution and competitiveness-induced output effects dominate the direct negative efficiency effect (by which any given level of output can now be produced with less energy input). The key point is that electricity production is itself very energy intensive - 26% and 29% of the input requirements of the renewable and non-renewable sectors respectively. [The reader is reminded that these are vertically integrated sectors, incorporating all generation/production and distribution activities; in the case of the renewable sector, energy is an important input to distribution activies (according to the experimental Scottish input-output data used to identify these sectors)]. This compares to under 3% for the other three energy sectors. Therefore the biggest fall in the price of output is observed in the electricity sectors, particularly the non-renewable sector, leading to a substitution away from fuels and in favour of electricity. Moreover, and in particular, there is large stimulus to export demand as the price of Scottish electricity falls relative to electricity produced elsewhere in the UK.

Insert Figure 3

Figure 3 shows the change in value-added in each of the energy sectors over time. The pattern of initial falls in value-added and then recovery observed in the fuel sectors is not that surprising since elasticities tend to increase through time as capital stocks (and population) adjusts. (The suggestion is, for example, that demand for coal is price-inelastic in the short-run, but elastic over the longer-term.) Note that the main factor driving the recovery in the coal and gas sectors is intermediate demand from the non-renewable electricity generation sector. However, value-added in the electricity industries increases immediately, indicating the presence of elastic general equilibrium demand for these sectors' outputs.

Insert Figure 4

It is important to note that in the simulations reported here we assume that there are no long-run constraints on the capacity of the coal and gas supply sectors, or on the adjustment of capital stock in the non-renewable electricity generation sector. However, it may be useful in future research to examine the impacts of introducing constraints on investment, particularly in terms of coal-fired power stations (of which only three remain in Scotland).

The impacts on "sustainability" indicators identified in Section 3 are striking. First, the growth in both energy consumption and production in Scotland can be seen in Figure 4. While the amount of electricity *consumed* in Scotland initially falls (as explained above, initially the output of the electricity sectors increases as a result of increased *export* demand), by period 15 it has risen above the base year value. Non-electricity energy consumption follows a similar pattern, with the rise above the base year value occurring one period later. The second energy indicator set out in Section 3 is the share of electricity generated from renewable sources. Figure 4 shows that this falls from the outset due to the fact that the more energy intensive non-renewable electricity sector receives a greater stimulus as a result of the increase in energy efficiency. So the movements in key resource productivity indicators are "perverse": an improvement in energy efficiency causes indicator changes that suggest a movement towards a *less* sustainable development path, according to these indicators.

Secondly, Figure 4 shows the impact of the energy efficiency shock on the energy and resource productivity indicators. Here we take Y as Scottish GDP and, partly due to the problem of differing units of measurement, define one variant Y/E(1) as GDP divided by tonnes of (local and imported) fuel (non-electricity energy inputs) consumed in Scotland, measured in tonnes of oil equivalent. We define a second variant Y/E(2) as GDP divided by electricity consumption in Scotland (measure in gigawatt hours). Typically, a rise in the value of this ratio would be taken as a move in the direction of more sustainable development, but Figure 4 shows that, after an initial rise both of these begin to fall, as the proportionate change in energy consumption is greater than the increase in GDP resulting from the efficiency shock, a phenomenon that can, of course, only arise in the presence of significant backfire.

The increase in energy consumption naturally has implications for the other sustainability indicators identified earlier, in particular, for the ratio of GDP to CO2 emissions (Y/P). Our results show that while the value of this indicator initially rises (i.e. improves) due to the decline in energy consumption in the first 15 years after the introduction of the efficiency shock, by period 30 it is less than in the base year. This is reflected in the fact that in period 30 the growth in CO2 emissions starts to outstrip the growth in GDP (see Figure 5).

Insert Figure 5

In summary, our results suggest that, in the case of a policy focussed on a single, open regional economy, an improvement in energy efficiency may generate a stimulus to energy production and consumption and to overall economic activity, and a deterioration in environmental indicators. As Figure 4 shows, rebound exists for both electrical and non-electrical energy used in the short run, since the fall in consumption is less than the 5% improvement in efficiency; whilst backfire occurs in the longer term, since energy consumption actually increases above the baseline. The general equilibrium price elasticity of demand for energy in Scotland is greater than unity.

Sensitivity analysis around central case scenario

Our theoretical analysis suggested a number of sets of key parameters that may be important in governing the extent of rebound/ backfire: elasticities of substitution of energy for other inputs; price elasticities of demand for outputs; the elasticities of supply of other factors; the energy intensity of the sectors .The first two sets of parameters are readily identifiable in AMOSENVI and we explore their impact below. We have already effectively conducted a sensitivity analysis on the elasticities of supplies of other factors given that these elasticities vary directly with duration of the time interval of the analysis, which we have varied (both conceptually and on a period-by-period basis). The energy intensity of sectors is embedded in the base year SAM. However, by selectively introducing the energy efficiency shock in different subsets of sectors we can infer the impact of intersectoral differences in energy intensities. In the remainder of this sub-section we outline the economic, energy and environmental impacts of varying key parameter values, and closure assumptions.

Varying key substitution elasticities in the production function

The parameters that would be expected on the basis of our theoretical discussion to impact most strongly on the results are the elasticities of substitution: between energy and non-energy intermediates to determine the local composite intermediate good (see Figure 1), which we will refer to as σ_L; and between value-added and intermediate inputs to determine gross output, which we will refer to as σ_Q. In the central case both of these parameters take the value of 0.3 in all sectors. For sensitivity, we vary each of these parameters (independently) to 0.1 and 0.7. For conciseness, we focus on long run equilibria only. In the central case we observe backfire.

Table 2 shows the long run results from varying the elasticity of substitution between energy and non-energy intermediate inputs σ_L and the central case scenario. In the low elasticity case, it is more difficult for sectors to move away from the now relatively more expensive non-energy composite, and towards energy inputs that have experienced a fall in their relative price as a result of the improvement in energy efficiency. While the structure of production functions here is rather more complex than the case considered by Saunders (e.g. 2000a,b), and our results reflect the consequences of a full general equilibrium model, it is instructive to note that all of the results in Table 2 are characterised by the presence of backfire, even for very low substitution elasticities of energy for other inputs (of 0.1). Quite clearly, high elasticities of substitution of energy for other inputs are not a necessary condition for backfire. However, the extent of backfire does vary directly with the value of this elasticity: total electricity consumption increases by just over 0.47% in the low elasticity case, but by over 2.5% the high elasticity case. The high elasticity case produces an electricity rebound effect of 168.9% while, with low elasticities, rebound is 113%. Similarly, for non-electricity energy consumption the increase in consumption is largest, 1.76%, in the high elasticity case, and lowest, 0.34%, in the low elasticity case. The corresponding non-electricity energy rebound effects are just over 151% and just under 110% respectively.

Table 3 shows the long-run results from varying the elasticity of substitution between value-added and intermediate inputs, σ_Q. This is the point at the very top level of the production hierarchy used in AMOSENVI (see Figure 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, so in our production hierarchy it is another determinant of the overall ease of substitution of energy for other inputs. Total energy consumption displays significant backfire effects again, even in the low elasticity case, though these are greater the higher the value of the elasticity of substitution between value added and intermediate inputs. However, the variation in the backfire effects for both electricity and non-electricity consumption around the central case is significantly less than is the case in Table 2.

Varying the export demand elasticities

Tables 4 and 5 show the long run effects and the central scenario results from varying the export demand elasticities for exports to the rest of the UK (RUK) and rest of the world (ROW) respectively, which are key determinants of the price-responsiveness of the demand for the outputs of these sectors. In the base case, these demand elasticities were set at 5 for the electricity sectors (E), and 2 for the other energy sectors (O) and the non-energy sectors (N). (The relatively high value of 5 was initially set for the electricity sectors to reflect the assumption that electricity is a fairly homogenous commodity.) 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 Scottish price reductions. In the ROW case (Table 5), 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 to ROW. Only when the export elasticities in all sectors are set to 5 do we observe a significant variation in the results for GDP, employment, energy use and the estimated rebound (backfire) effects.

However, more variation is observed in the RUK case (Table 4). With the exception of 'Gas', all of the energy sectors export a significant share of their output to RUK (Coal extraction exports 12% of its output, oil refining and distribution and nuclear export 51% and the two electricity sectors export 31%). GDP increases range from 0.61% with all RUK export demand elasticities set at 2, to 1.09% with all elasticities at 5. The variation in total energy consumption is also large for both electricity and non-electricity consumption. Crucially, the impact on overall energy consumption varies significantly with the RUK export demand elasticities: the results range from a *decrease* in energy consumption of -0.65% for electricity and –0.78% for non-electricity to increases of 1.32% and 1% respectively. Where a decrease in energy consumption occurs there is no backfire, though there are still very large rebound effects (relative to others' findings) of 82.2% for electricity consumption and 77.4% for non-electricity consumption.

Recall that the responsiveness of output demands to relative prices do not feature at all in Saunders (2000a,b; 2006) analyses, with all the emphasis being placed on production substitution elasticities. It is quite clear from our own results, that in an open economy context the responsiveness of goods demands to relative prices are important in governing the scale of rebound and backfire effects, a result which emphasises the importance of our extensions to Saunders' theoretical analyses.

Results of varying the labour market closure

Table 6 shows the long run results of changing the labour market closure from the central case, where the real wage is determined by regional bargaining, to one where the nominal wage is determined at the national level, as it would be under a national bargaining system in which the region effectively becomes a nominal wage-taker. There is a significant variation in all the key macroeconomic results, reflecting the more limited expansion in response to the positive supply-side shock due to the fact that the nominal wage is invariant in the face of the fall in prices, so that real wages rise. The more limited expansion in economic activity inhibits the rise in both types of energy consumption, and the consequent backfire effects are smaller. However, the changes to the central case result on the degree of backfire are small for both electricity and non-electricity energy..

Varying the sectors targeted with the energy efficiency shock

The final set of sensitivity analyses test the implications of variations in sectoral energy supply and use characteristics for the extent of rebound and backfire effects. In Table 7 we direct the 5% efficiency shock at different sub-sets of sectors. The long run results of the central case scenario, where all 25 sectors are targeted are shown in column 1. In column 2 the shock is targeted at the 5 energy supply sectors only and in column 3 the non-energy sectors only are shocked (and the results in these two columns sum approximately to those in column 1). The effects on the key macroeconomic variables are smaller in column 2 because the shock is more limited in scope. However, the increases in both types of energy consumption are larger than in the base case where all 25 production sectors are targeted with the energy efficiency improvement (column 1), with the result that the backfire effects are appreciably larger. Again, this is primarily due to what happens to the electricity sectors: in column 5, where the efficiency shock is targeted at the Oil and Gas supply sectors, we observe a slight drop in both types of energy consumption and there is no backfire effect (although there are still significant rebound effects). In contrast, column 3 shows the results of an increase in efficiency only in the other twenty, non-energy supply sectors. Again, the effects on the key macroeconomic variables are smaller due to the more limited shock. However, not only do we observe a decrease in both types of energy consumption at the aggregate level, note that for the first time this is larger in the case of electricity consumption and the associated rebound effect, 41.9% is smaller than that for non-electricity consumption, 60.2%. Nonetheless, the results of this simulation show that there are still significant rebound effects when the shock is confined to energy consumption rather than energy supply sectors.

Note also that the presence and magnitude of the economy-wide rebound effect does not depend only on the energy intensity of production. For example if we shock the most electricity-intensive production sector only – Sector 9 'Mfr – Chemicals etc' the long-run decrease in aggregate energy consumption is smaller (0.05% compared to 1.21% in Column 3 when all 20 sectors are shocked), with the result that the electricity rebound effect is larger (54.63%). (We do not present the full results of these two shocks as the macroeconomic effects are negligible in the presence of such small disturbances.) However, if we shock the least electricity intensive production sector only – Sector 3 'Sea Fishing' – while electricity consumption in this sector falls in every period, there is a small *increase* in aggregate electricity consumption in the long-run of 0.0008%. This is mainly driven by increases in imported and domestic electricity used by the 'Transport' and 'Mfr – Textiles and Clothing' sectors, both of which are direct intermediate suppliers of inputs to the 'Sea Fishing' sector. While the increase in aggregate energy consumption is small, given that the shock is applied to such a small share of total energy use, it means that there is in fact a backfire effect in terms of electricity consumption even when the shock is limited to the least (directly) electricity intensive production sector in the economy. This demonstrates why a general equilibrium framework is essential is assessing the nature and scope of rebound effects, even when improvements in energy efficiency are focussed in a single sector/activity.

Finally, we focus specifically on the implications for the electricity rebound effect if the efficiency shock only takes place in sectors that are heavier users of gas and oil than of electricity (coal use is so small that we do not give it separate attention here). In column 4 of Table 7, the shock is introduced to all five sectors in the economy that are heavier users of gas and oil than of electricity, then in columns 5 and 6 respectively we split these into energy supply and non-energy supply sectors. In both cases we note that backfire does not occur for either type of energy consumption, although significant rebound effects still occur. However, in the case of the energy supply sectors in column 5, the electricity rebound effect is still significantly higher than the non-electricity rebound effect. The opposite is true for the non-energy supply sectors.

6. Conclusions

In this paper 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 ineffective in reducing energy consumption, and this served further to emphasise the importance of the time interval under consideration. In particular, we show that Saunders' (2000a, b) theoretical analyses require augmentation in an open-economy context. We argued that zero rebound, at the macro level, is highly unlikely: the key question is then empirical: how much rebound will happen in a given case, and what determines its extent?

In our central case, we find that an improvement in energy efficiency results in an initial fall in energy *consumption*, but this is eventually reversed: positive output and substitution effects associated with lower effective energy prices ultimately outweigh the direct efficiency effect. There is a significant rebound effect immediately, but this gradually increases through time, eventually resulting in backfire in terms of electricity consumption. In terms of electricity *production* backfire is immediately apparent. These results are not what advocates of enhancing resource productivity would anticipate, or wish for, and it is potentially important for the appropriate conduct of energy policy. We then set these results in the contexts of "sustainability indicators" suggested by the UK and Scottish governments; these include the ratio of GDP to energy use, and the ratio of GDP to CO2 emissions. Again, the energy efficiency shock sends both of these indicators in the wrong direction. Our sensitivity analysis shows that emphasis of Saunders (2000a,b) analyses on the overwhelming importance of the elasticity of substitution of energy for other inputs is unduly restrictive: both rebound and backfire can occur even when this elasticity is very low (though they are increasing in its absolute value).

The results presented here imply that in order to ensure that improvements in local sustainability indicators result from improvements in resource productivity it would be necessary to counteract by some means the positive competitiveness effects that occur due to the fall in the price of output in energy intensive sectors. This could be achieved either by the introduction of a tax on energy use or by seeking to introduce the efficiency improvements at the national level so that the *relative* price effect is limited since currently there is limited international trade in electricity with the UK. The former option is not currently available to the Scottish Parliament (since its tax-varying powers are confined to variations in the basic rate of income tax), and exploration of the latter would require an explicity interregional model of the UK. Of course, from a global, or even UK-wide perspective, the displacement of electricity generated within RUK and ROW by electricity generated more carbon-efficiently due to the generation mix within Scotland does (probably) generate an improvement in terms of global GHG emission. But this may come at the expense of worsening air quality, due say to higher PM10 emissions, locally. This suggests a trade-off between local and global environmental concerns resulting from improvements in resource productivity.

Some important caveats are, however, in order. First, our regional perspective is important: the presence of interregional trade in energy (and electricity in particular) in the UK is significant in leading to a price-elastic general equilibrium demand for energy in Scotland. The result would be less likely if the energy efficiency increase were to be mandated throughout the UK.[13] Secondly, the results are unlikely to be associated with a deterioration in UK environmental indicators, as the expansion of Scottish electricity exports occurs at the expense of less carbon-efficient electricity production in RUK. We have also noted that regions have been given an important role to play, both in energy efficiency and sustainability policy by national governments. However, it is not at all clear that the UK government has yet evolved a coherent policy on meeting environmental targets that takes proper account of increasing autonomy at the regional level in the presence of interregional environmental spillovers. Third, the message for sustainability depends on the information content of the indicators used here: whilst an improvement in the ratio of GDP to either resource use or pollution emissions would be counted by most as being helpful in terms of improving sustainability, they do not constitute either necessary or sufficient conditions for sustainability (and perhaps not surprisingly, are particularly problematic if sustainability constraints are related to the absolute levels of energy use or pollutants). Many components of an economic indicator of sustainability – such as Genuine Savings – are missing from this analysis, whilst others would argue that such economic indicators are themselves deficient (Pezzey et al 2006).

We believe that the key point that this paper makes is an interesting one: focussing on improvements in resource productivity as a keystone of sustainability policy may produce undesirable impacts in terms of energy used and 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 – see Bruvoll et al (2003) for an endogenous treatment of policy). 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. 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. Furthermore, our analysis emphasises the importance of adopting a long-term perspective in evaluating policies: a short-term focus is likely to foster inappropriate inferences about policy impacts. However, what energy efficiency stimuli do create is 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.

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APPENDIX 1. A CONDENSED VERSION OF AMOSENVI

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	$L = \bar{L}$
(6) Consumer price index	$cpi = \sum_i \theta_i\, pq_i + \sum_i \theta_i^{RUK}\, \bar{pq}_i^{RUK} + \sum_i \theta_i^{ROW}\, \bar{pq}_i^{ROW}$
(7) Capital supply	$K_i^s = \bar{K}_i^s$
(8) Capital price index	$kpi = \sum_i \gamma_i\, pq_i + \sum_i \gamma_i^{RUK}\, \bar{pq}_i^{RUK} + \sum_i \gamma_i^{ROW}\, \bar{pq}_i^{ROW}$
(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	$Y = \Psi_n N w_n (1 - t_n) + \Psi_k \sum_i w_{k,i}(1 - t_k\bar{)} + \bar{T}$
(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 (CO2)	$POL_{CO2} = \sum_i \left[\sum_j (e_{i,f} \cdot f_{i,f}) + (g_i . \kappa_i) + h_i\right] Q_i$
Multi-period model	**Stock up-dating equations**
(23) Labour force	$L_t = L_{t-1} + nmg_{t-1}$
(24) Migration	$\frac{nmg}{L} = nmg\left(\frac{w_n(1-t_n)}{cpi}, \frac{w_n^{RUK}(1-t_n)}{cpi^{RUK}}, u, u^{RUK}\right)$
(25) 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 AMOSENVI: 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

$\mathbf{pq}$	vector of commodity prices
$\mathbf{pv}$	price of value added
$\mathbf{t}_n$, $\mathbf{t}_k$	average direct tax on labour and capital income
$\mathbf{u}$	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 CO2
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. Sectoral breakdown of the 1999 Scottish AMOSENVI model

		IOC
1	AGRICULTURE	1
2	FORESTRY PLANTING AND LOGGING	2.1, 2.2
3	FISHING	3.1
4	FISH FARMING	3.2
5	Other mining and quarrying	6,7
6	Oil and gas extraction	5
7	Mfr food, drink and tobacco	8 to 20
8	Mfr textiles and clothing	21 to 30
9	Mfr chemicals etc	36 to 45
10	Mfr metal and non-metal goods	46 to 61
11	Mfr transport and other machinery, electrical and inst eng	62 to 80
12	Other manufacturing	31 to 34, 81 to 84
13	Water	87
14	Construction	88
15	Distribution	89 to 92
16	Transport	93 to 97
17	Communications, finance and business	98 to 107, 109 to 114
18	R&D	108
19	Education	116
20	Public and other services	115, 117 to 123
	ENERGY	
21	COAL (EXTRACTION)	4
22	OIL (REFINING & DISTR OIL AND NUCLEAR)	35
23	GAS	86
	ELECTRICITY	85
24	Renewable (hydro and wind)	
25	Non-renewable (coal, nuke and gas)	

APPENDIX 3. CO_2 Pollution Coefficients for Scotland in 1999

	Tonnes energy-related CO_2 per £1million purchases of:					Tonnes CO_2 (non-energy) per £1million total output
Polluting sector/final demand category:	Local coal	Local oil-based fuels	Local gas	Imports from RUK	Imports from ROW	
Agriculture	51719	23188	22282	284	100	0
Forestry Planting and Logging	51719	24194	22282	939	518	0
Sea Fishing	51719	23279	22282	311	5513	0
Fish Farming	51719	23279	22282	0	0	0
Other mining and quarrying	52317	23228	22282	55	302	0
Oil and gas extraction	52317	23267	27692	770	3691	187
Mfr food, drink and tobacco	52559	23327	22282	185	9	0
Mfr textiles and clothing	52559	23290	22282	43	10	0
Mfr chemicals etc	52559	23271	21512	152	0	0
Mfr metal and non-metal goods	55484	22724	22282	152	1	118
Mfr transport and other machinery, electrical and inst eng	52559	23139	22282	41	1	0
Other manufacturing	52559	23259	22282	478	0	0
Water	52317	22895	22282	209	453	0
Construction	52317	23146	22282	138	6	0
Distribution	52317	23007	22282	938	17	0
Transport	52317	19127	22282	2132	127	0
Communications, finance and business	52317	22941	22282	130	788	0
R&D	52317	22758	22282	0	0	0
Education	50840	23173	22282	984	80	0
Public and other services	50866	23254	22282	352	624	0
Coal (Extraction)	0	26923	22282	5	0	0
Oil (refining and distribution, nuclear)	17160	21354	22282	0	0	310
Gas	52317	1349	22282	128	0	0
Electricity - Renewable (hydro and wind)	51466	22933	22282	1323	0	0
Electricity - Non-renewable (coal, nuke and gas)	51466	4910	22282	6147	0	0
Households	49633	22672	22282	248	142	0
Tourists	49633	22672	22282	113	338	0

Figure1. Production structure of each sector i in the 25 sector/commodity AMOSENVI KLEM framework

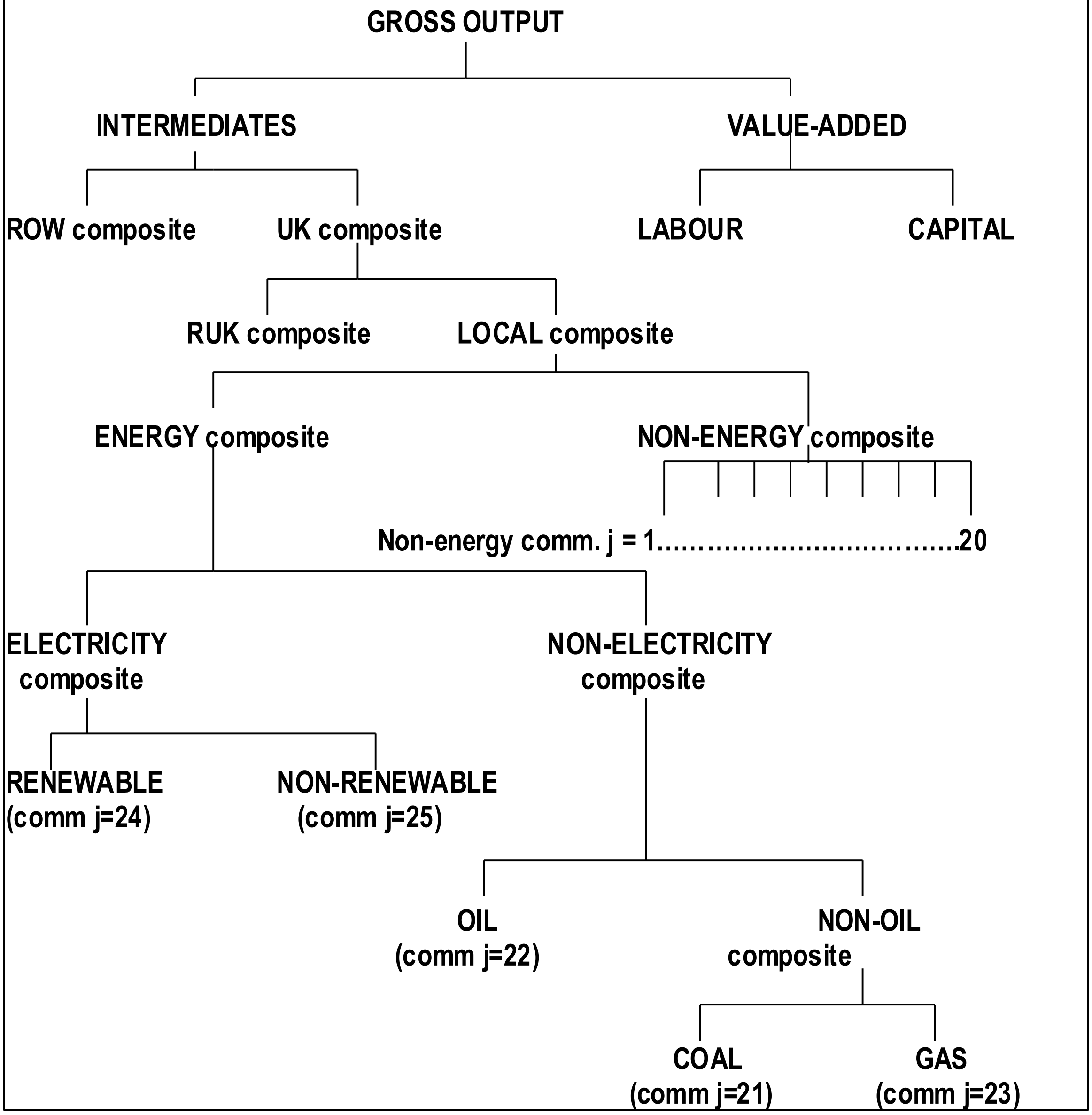

Table 1. The Aggregate Impact of a 5% Increase in Energy Efficiency in all Production Sectors
(Percentage changes from base)

	Short-run	Medium-run	Long-run
GDP (income measure)	0.06	0.10	0.88
Consumption	0.19	0.22	0.80
Investment	0.29	0.36	1.03
Exports	0.21	0.23	0.96
Imports	0.03	0.05	0.28
Nominal before-tax wage	0.12	0.02	-0.22
Real T-H consumption wage	0.09	0.00	0.00
Consumer price index	0.02	0.02	-0.22
Total employment (000's):	0.10	0.16	0.80
Unemployment rate (%)	-0.83	0.00	0.00
Total population (000's)	0.00	0.16	0.80
Total electricity consumption	-1.33	-1.30	1.15
Electricity rebound effect (%)	63.4	64.4	131.5
Total non-electricity energy consumption	-1.08	-1.05	0.81
Non-electricity energy rebound effect (%)	68.6	69.3	123.5

Figure 2.Change in output in Scottish production sectors in response to a 5% increase in energy efficiency in all production sectors

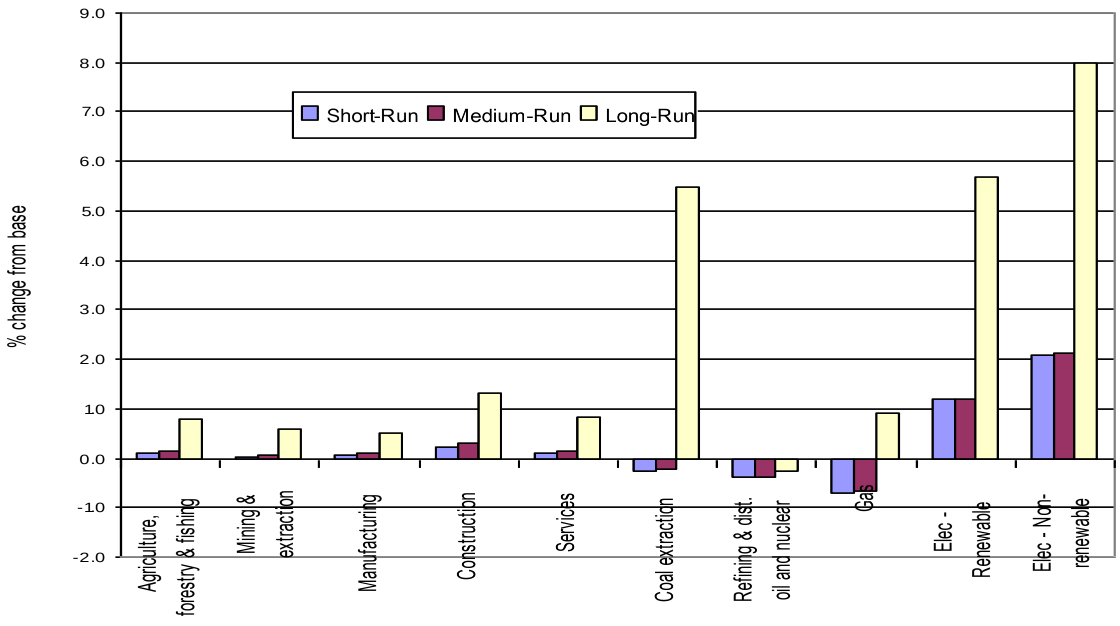

Figure 3. Change in sectoral value added in Scottish energy sectors in response to a 5% increase in energy efficiency in all production sectors

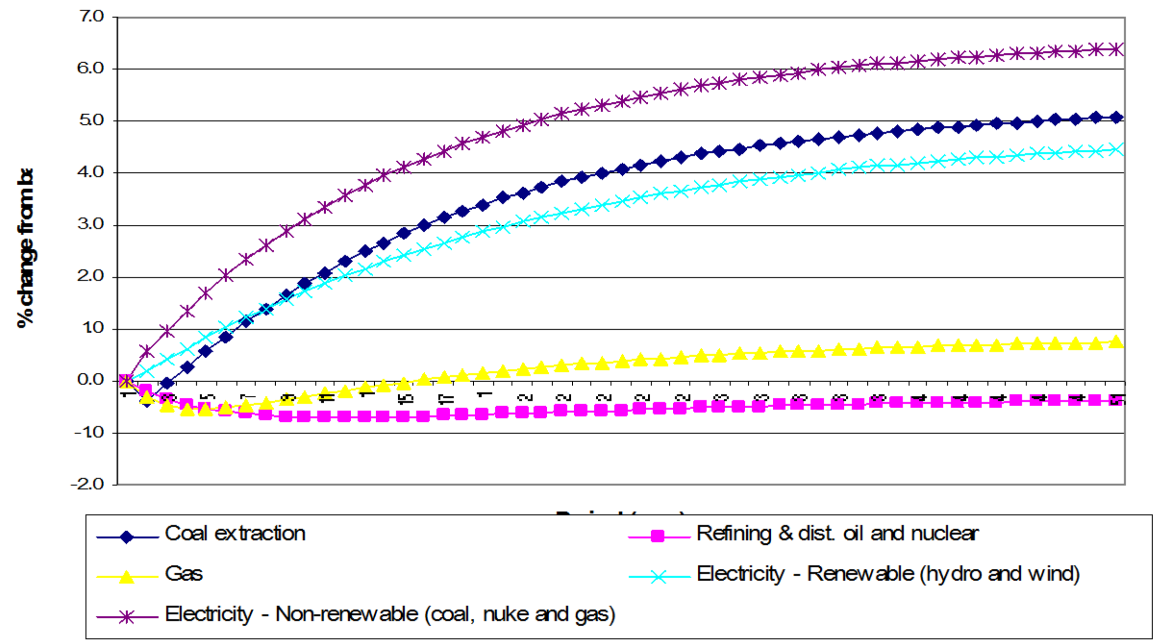

Figure 4. Impact of a 5% increase in energy efficiency in all production sectors on energy indicator variables

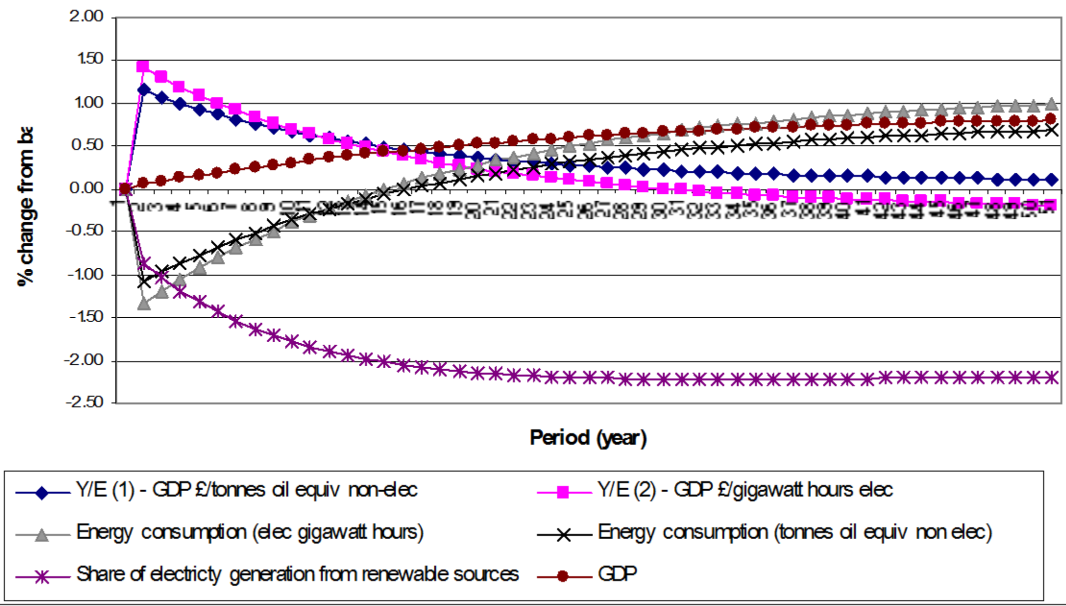

Figure 5. Impact of a 5% increase in energy efficiency in all production sectors on environmental indicator variables

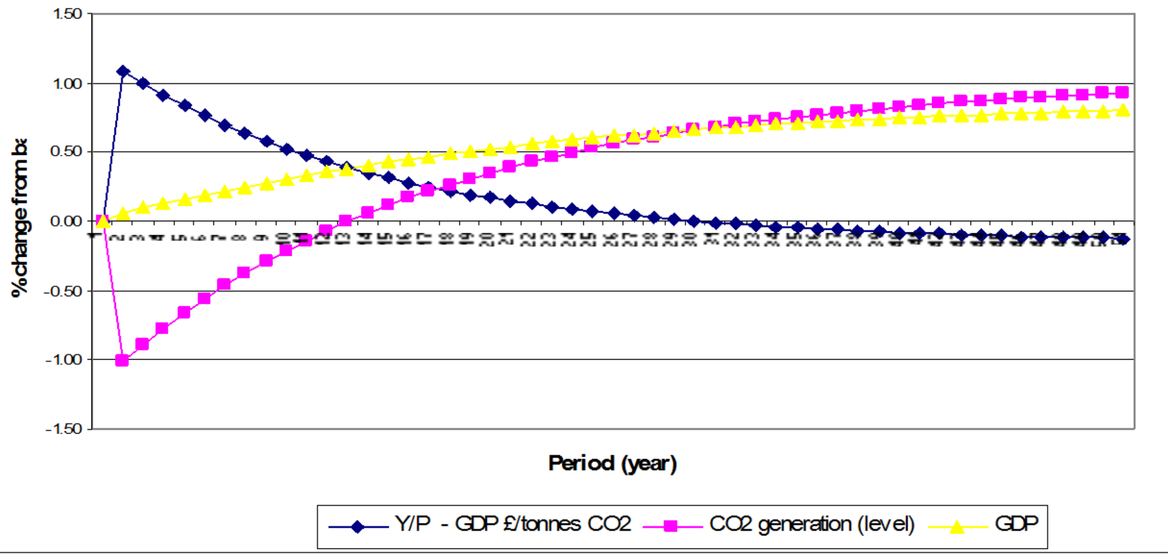

Table 2. Long-Run Impact of Changing Elasticity of Subsitution Between Energy and Non-Energy Intermediate Inputs (the SIGMAL parameter) (Percentage changes from base year)

	Low (0.1)	Central (0.3)	High (0.7)
GDP (income measure)	0.880	0.878	0.874
Consumption	0.798	0.795	0.787
Investment	1.024	1.028	1.038
Exports	0.953	0.956	0.962
Imports	0.283	0.283	0.283
Nominal before-tax wage	-0.216	-0.217	-0.219
Real T-H consumption wage	0.000	0.000	0.000
Consumer price index	-0.216	-0.217	-0.219
Total employment (000's):	0.812	0.803	0.785
Unemployment rate (%)	0.000	0.000	0.000
Total population (000's)	0.812	0.803	0.785
Total electricity consumption	0.473	1.148	2.514
Electricity rebound effect (%)	113.0	131.5	168.9
Total non-electricity energy consumption	0.337	0.806	1.756
Non-electricity energy rebound effect (%)	109.8	123.5	151.1

Table 3. Long-Run Impact of Changing Elasticity of Subsitution 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)	0.893	0.878	0.848
Consumption	0.807	0.795	0.771
Investment	1.050	1.028	0.985
Exports	0.954	0.956	0.962
Imports	0.279	0.283	0.289
Nominal before-tax wage	-0.217	-0.217	-0.218
Real T-H consumption wage	0.000	0.000	0.000
Consumer price index	-0.217	-0.217	-0.218
Total employment (000's):	0.813	0.803	0.784
Unemployment rate (%)	0.000	0.000	0.000
Total population (000's)	0.813	0.803	0.784
Total electricity consumption	1.009	1.148	1.427
Electricity rebound effect (%)	127.6	131.5	139.1
Total non-electricity energy consumption	0.691	0.806	1.037
Non-electricity energy rebound effect (%)	120.1	123.5	130.2

Table 4. Long-run Impact of Changing the RUK Export Demand Elasticities (the RHOUK parameters) (Percentage changes from base year)

	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)	0.878	0.608	0.884	1.089
Consumption	0.795	0.574	0.799	0.981
Investment	1.028	0.665	1.036	1.255
Exports	0.956	0.584	0.967	1.248
Imports	0.283	0.062	0.290	0.472
Nominal before-tax wage	-0.217	-0.217	-0.217	-0.217
Real T-H consumption wage	0.000	0.000	0.000	0.000
Consumer price index	-0.217	-0.217	-0.217	-0.217
Total employment (000's):	0.803	0.599	0.807	1.002
Unemployment rate (%)	0.000	0.000	0.000	0.000
Total population (000's)	0.803	0.599	0.807	1.002
Total electricity consumption	1.148	-0.648	1.153	1.318
Electricity rebound effect (%)	131.5	82.2	131.6	136.1
Total non-electricity energy consumption	0.806	-0.777	0.814	0.998
Non-electricity energy rebound effect (%)	123.5	77.4	123.7	129.1

Table 5. Long-run Impact of Changing the ROW Export Demand Elasticities (the RHOW parameters)
(Percentage changes from base year)

	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)	0.878	0.878	0.879	1.041
Consumption	0.795	0.795	0.795	0.938
Investment	1.028	1.028	1.029	1.210
Exports	0.956	0.956	0.957	1.207
Imports	0.283	0.283	0.283	0.463
Nominal before-tax wage	-0.217	-0.217	-0.217	-0.217
Real T-H consumption wage	0.000	0.000	0.000	0.000
Consumer price index	-0.217	-0.217	-0.217	-0.217
Total employment (000's):	0.803	0.803	0.804	0.957
Unemployment rate (%)	0.000	0.000	0.000	0.000
Total population (000's)	0.803	0.803	0.804	0.957
Total electricity consumption	1.148	1.148	1.148	1.288
Electricity rebound effect (%)	131.5	131.5	131.5	135.3
Total non-electricity energy consumption	0.806	0.806	0.807	0.949
Non-electricity energy rebound effect (%)	123.5	123.5	123.5	127.6

Table 6. Long-run Impact of Changing the Specification of the Labour Market
(Percentage changes from base year)

	Regional Wage Bargaining	National Wage Bargaining
GDP (income measure)	0.88	0.66
Consumption	0.80	0.67
Investment	1.03	0.81
Exports	0.96	0.76
Imports	0.28	0.24
Nominal before-tax wage	-0.22	0.00
Real T-H consumption wage	0.00	0.14
Consumer price index	-0.22	-0.14
	0.00	0.00
Total employment (000's):	0.80	0.58
Unemployment rate (%)	0.00	0.11
Total population (000's)	0.80	0.59
Total electricity consumption	1.148	0.860
Electricity rebound effect (%)	131.5	123.6
Total non-electricity energy consumption	0.806	0.588
Non-electricity energy rebound effect (%)	123.5	117.1

Table 7. Long-run Impact of Varying Target of Energy Efficiency Shock
(Percentage changes from base year)

	All sectors	Energy supply sectors	Non-energy supply sectors	Heavier users of gas and oil	Heavier users of gas and oil (energy supply)	Heavier users of gas and oil (non-energy supply)
	1-25	21-25	1-20	2,3,16,22,23	22,23	2,3,16
GDP (income measure)	0.88	0.58	0.30	0.034	0.009	0.024
Consumption	0.80	0.51	0.28	0.032	0.009	0.023
Investment	1.03	0.71	0.31	0.033	0.011	0.022
Exports	0.96	0.68	0.27	0.037	0.007	0.030
Imports	0.28	0.28	0.00	0.006	0.000	0.006
Nominal before-tax wage	-0.22	-0.11	-0.11	-0.006	-0.003	-0.004
Real T-H consumption wage	0.00	0.00	0.00	0.000	0.000	0.000
Consumer price index	-0.22	-0.11	-0.11	-0.006	-0.003	-0.004
		0.00	0.00	0.000	0.000	0.000
Total employment (000's):	0.80	0.50	0.30	0.032	0.009	0.023
Unemployment rate (%)	0.00	0.00	0.00	0.000	0.000	0.000
Total population (000's)	0.80	0.50	0.30	0.032	0.009	0.023
Total electricity consumption	1.15	2.35	-1.21	-0.05	-0.01	-0.04
Electricity rebound effect (%)	131.5	249.7	41.9	52.4	72.1	45.7
Total non-electricity energy consumption	0.81	1.61	-0.82	-0.17	-0.03	-0.14
Non-electricity energy rebound effect (%)	123.5	216.3	60.2	63.9	56.8	65.1

Endnotes

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[1] By the general equilibrium demand curve for energy we mean the relationship between the price of energy and the quantity demanded, allowing incomes, and the prices and outputs of all other goods to adjust. That is to say, if the price of energy could be fixed exogenously, this would be the corresponding general equilibrium level of demand.

[2] We are grateful to an anonymous referee for clarifying this distinction to us.

3 AMOS is an acronym for a macro-micro model of Scotland. AMOSENVI is a variant with an appropriate sectoral disaggregation and set of linked pollution coefficients, developed specifically to allow us to investigate environmental impacts.

4 In AMOSENVI, Scotland is treated as a self-governing economy, in the sense that there is only one consolidated government sector. Central government activity is partitioned to Scotland and combined with local government activity.

5 Parameter α is calibrated so as to replicate the base period (as is β in equation [6]). 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,

6 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.

7 Note that there is also debate in the CGE literature regarding the use of nested functional forms because of the imposition of separability assumptions (see Turner, 2002 for a review of this debate). To avoid this problem, Hertel & Mount (1985), Depotakis & Fisher (1988) and Li & Rose (1995) adopt some type of flexible functional form (FFF) production function with dual Generalised Leontief or Translog cost functions . The idea is to make the production function as flexible possible by minimising the number of prior assumptions about its form. In practice, however, this argument over whether to use CES or FFF is likely to boil down to a trade off between flexibility and tractability. In a model with a highly detailed treatment of energy, Naqvi (1998) argues that separability assumptions are necessary from a practical point of view, where there are multiple inputs and/or multiple sectoral outputs. Indeed, as noted by Turner (2002), Hertel & Mount (1985), Depotakis & Fisher (1988) and Li & Rose (1995) all choose to employ two levels of cost functions, with substitution between KLEM inputs on the first level, then within the energy and/or materials aggregates on the second level. Thus, while advocating the employment of flexible functional forms to reduce the number of restrictions, including separability, that are imposed on the production function by use of nested CES functions are in fact prepared to accept *some* separability assumptions.

8 Note that this treatment of pollution generation from the combustion in Scotland of imported energy inputs implies the assumption that the composition of imports from RUK and ROW is fixed.

9 We investigate the existence and implications of an 'environmental trade balance' between Scotland and the rest of the UK in terms of CO2 emissions in McGregor *et al* (2008).

[10] In research currently being undertaken, we attempt to vertically disaggregate the electricity sector by carrying out our own surveys of companies in the sector. See the Energy Research pages at http://www.fraser.strath.ac.uk for details of this work (funded by the EPSRC under the Supergen Marine Consortium (grant reference GR/S26958/01).

11 Indicators 12 and 13 in Scottish Executive (2002a, 2003)

12 As noted above, we use extended experimental data provided by the Input-Output branch of the Scottish Executive to disaggregate the Electricity sector in the Scottish IO tables for 1999. The renewable source sectors identified in this data are hydro and wind. The non-renewable source sectors are coal, gas and nuclear.

[13] More generally, in our single region model the rest of the UK is exogenous. In future work we hope to expand to an interregional framework for the UK so that we can examine the impacts of changes in energy efficiency in one UK region on activity in other regions (crowding out effects etc).