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ANALYSIS

Do increases in energy efficiency improve environmental quality and sustainability?

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ABSTRACT

Governments world-wide increasingly see energy efficiency as an important aspect of sustainability. However, there is a debate in the literature as to whether the impact of improved energy efficiency on reducing energy use might be partially, or more than wholly, offset through “rebound” and “backfire” effects. 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 for Scotland a general improvement in energy efficiency in the production sectors of the economy initially produces rebound effects that eventually grow into backfire. Energy use ultimately increases in response to an efficiency gain and the ratio of GDP to CO₂ emissions falls. The economic factors underpinning rebound effects are straightforward: energy efficiency improvements result in an effective cut in energy prices, which produces output, substitution, competitiveness and income effects that stimulate energy demands. However, the presence of strong rebound or even backfire does not mean that efficiency-enhancing policies are irrelevant: rather it suggests that such policies operating alone are insufficient to generate environmental improvements. The implication is that a co-ordinated portfolio of energy policies is required.

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1. Introduction and background

In this paper we build on the energy economics literature concerning “rebound” and “backfire” effects (Khazzoom, 1980; Brookes, 1990; Herring, 1999; Birol and Keppler, 2000; Saunders, 2000a,b). Specifically we explore the theoretical conditions under which improvements in energy efficiency result in less than proportionate reductions, or even increases, in energy consumption. This theoretical argument is supported

by simulation evidence from a regional, energy–economy–environment computable general equilibrium (CGE) model of Scotland.

We aim to inform the policy debate in the UK, where sustainable development is a key objective of government policies at the national and regional levels. Improvements in energy efficiency have been suggested as both a measure of progress towards sustainable development and as a means of achieving sustainability (Cabinet Office, 2001). The popular

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interpretation of energy efficiency is “doing more with less”: that is, of reducing the energy requirements associated with a given level of economic activity. This issue is also receiving increased emphasis in a regional development context with, for example, the Scottish Parliament recently reaffirming its commitment to sustainable development (Scottish Executive, 2002b, 2003, 2005; Scottish Government, 2007). In the UK, the success of national sustainability programmes will depend upon policy delivered at the regional level; the region therefore appears to be a very relevant spatial focus for policy evaluation.

In Section 2 we explain rebound and backfire effects. We present our own analysis of the likely ramifications in a system-wide context and summarise the previous empirical results. In Section 3 we give a general introduction to our energy–economy–environment CGE model of Scotland, AMO-SENV. In Section 4 we present the results of simulating an across-the-board stimulus to energy efficiency in production, and provide sensitivity analysis around these central results. We conclude in Section 5.

2. Resource productivity enhancements, rebound and backfire

2.1. Theoretical considerations

It is instructive to provide a brief account of what has come to be known as the economy-wide rebound effect: that is, the economy-wide impact of an improvement in energy efficiency analysed within a general equilibrium framework. We begin by making a distinction between energy measured in natural units, E , and efficiency units, ϵ . The measure in natural units could be any physical measure of energy, e.g. kWh, BTU or PJ, while energy in efficiency units is a measure of the effective energy service delivered.¹ If there is energy-augmenting technical progress at a rate ρ , the relationship between the percentage change in physical energy use, $\dot{E}$, and the percentage change in energy use measured in efficiency units, $\dot{\epsilon}$, is given as:

$$\dot{\epsilon} = \rho + \dot{E} \quad (1)$$

Eq. (1) implies that for a 5% increase in energy efficiency, a fixed amount of physical energy will be associated with a 5% increase in energy measured in efficiency units. This means that in terms of the outputs associated with the energy use, the 5% increase in energy efficiency has an impact that is identical to a 5% increase in physical energy inputs, without the efficiency gain.

A central issue in the rebound analysis is the fact that any change in energy efficiency will have a corresponding impact on the price of energy, when that energy is measured in efficiency units. Specifically:

$$\dot{p}_{\epsilon} = \dot{p}_E - \rho \quad (2)$$

¹ This is very similar to the notion of the effective work that an energy supply can deliver as used in the energy literature (Berndt, 1978).

where p represents price and the subscript identifies energy in either natural (E) or efficiency (ϵ) units. Using the same numerical example, with constant energy prices in natural units, a 5% improvement in energy efficiency generates a 5% reduction in the price of energy in terms of efficiency units.

With physical energy prices constant, we expect a fall in the price of energy in efficiency units to generate an increase in the demand for energy in efficiency units. This is the source of the rebound effect. In a general equilibrium context:

$$\dot{\epsilon} = -\eta \dot{p}_{\epsilon} \quad (3)$$

where η is the general equilibrium price elasticity of demand for energy and has been given a positive sign. For an energy efficiency gain that applies across all uses of energy within the economy, the change in energy demand in natural units can be found by substituting Eqs. (2) and (3) into Eq. (1), giving:

$$\dot{E} = (\eta - 1)\rho \quad (4)$$

For an efficiency increase of ρ that applies to all energy use, rebound, R , expressed in percentage terms, is defined as:

$$R = \left[1 + \frac{\dot{E}}{\rho} \right] \times 100 \quad (5)$$

Rebound measures the extent to which the change in energy demand fails to fall in line with the increase in energy efficiency. Therefore where rebound is equal to 100%, a change in energy efficiency produces no change in energy use. Rebound values less than 100% but greater than 0% imply that there has been some energy saving as a result of the efficiency improvement, but not by the full extent of the efficiency gain. Therefore if a 5% increase in energy efficiency generates a 4% reduction in energy use, this corresponds to a 20% rebound. Rebound values greater than 100% imply positive changes in energy use, measured in natural units, and therefore indicate backfire.

If Eq. (4) is substituted into Eq. (5), the link between rebound and the general equilibrium elasticity of demand for energy is made absolutely clear:

$$R = \eta \times 100 \quad (6)$$

This conceptual approach is ideal for a fuel that is imported and where the natural price is exogenous or only changes in line with the demand measured in natural units. There are three important ranges of general equilibrium price elasticity values. If the elasticity is zero, the fall in energy use equals the improvement in efficiency and rebound equals zero. If the elasticity lies between zero and unity, so that energy demand is relatively price-inelastic, there is a fall in energy use but some rebound effect. If the elasticity is greater than unity, so that demand is relatively price-elastic, energy use increases with an improvement in energy efficiency. With a price-elastic demand for energy, rebound is greater than 100% and backfire occurs.

However, in an applied context, there are two problems that introduce greater complexity. The first is that energy is often produced domestically with energy as one of its inputs. This means that the price of energy in physical units will be endogenous, and will tend to fall with general improvements

in energy efficiency, giving further impetus for rebound effects. The second is that the general equilibrium elasticity of demand for energy is difficult to identify. The responsiveness of energy demand at the aggregate level to changes in (effective and actual) energy prices will depend on a number of key parameters and other characteristics in the economy, as our theoretical analysis in [Allan et al. \(in press\)](#) demonstrates. As well as elasticities of substitution in production, which tend to receive most attention in the literature (see [Broadstock et al., 2007](#), for an excellent review) these include: price elasticities of demand for individual commodities; the degree of openness and extent of trade (particularly where energy itself is traded); the elasticity of supply of other inputs/factors; the energy intensity of different activities; and income elasticities of energy demand (the responsiveness of energy demand to changes in household incomes). Thus, the extent of rebound effects is, in practice, always an empirical issue.

Before turning to the empirical evidence of rebound and backfire effects, a final point should be made. In the simulations reported in this paper we only improve energy efficiency in a subset of its uses: that is, in its use in production. The proportionate change in energy use is therefore $\frac{\Delta E_I}{E_I}$, where the I and T subscripts stand for total and industrial respectively. Similarly, the implied reduction in the price of energy in efficiency units only applies to its use in production, not in elements of final demand, such as household consumption. In these circumstances, the rebound effect should be calculated as:

$$R = \left[1 + \frac{\dot{E}_T}{\alpha p} \right] \times 100 \quad (7)$$

where α is the share of energy in industrial use, $\frac{E_I}{E_T}$.

2.2. Empirical evidence of rebound and backfire

[Sorrell \(2007\)](#) reviews the existing empirical evidence concerning the strength of the rebound effect. It is conventional to make a distinction between the direct and indirect effects of an improvement in energy efficiency on energy use. The direct effect is the impact in the activity to which the efficiency improvement applies. The indirect effects are the other, system-wide impacts associated with the changes in consumption and production of other goods and services that causally accompany the efficiency change.

Although numerous studies of the direct effect of particular efficiency improvements have been undertaken, the results are difficult to identify with any degree of accuracy. As [Sorrell \(2007, p. 25\)](#) states: “Measurement difficulties make estimation of direct rebound effects problematic at best and impossible at worst. For many energy services, the relevant data is simply unavailable, while for others the data must be either estimated or subject to considerable error.” On the other hand, very few studies attempt empirically to specifically identify the indirect effects. Existing information from this source is scant. Finally, the arguments made for total economy-wide impacts, such as the work of [Khazzoom \(1980\)](#), [Brookes \(1990\)](#) and [Saunders \(1992\)](#), are not, for [Sorrell \(2007, p.84\)](#) “based upon empirical estimates of rebound effects but instead ... upon stylised theoretical arguments and empirical

evidence that is both suggestive and indirect.” While overall there is much evidence for rebound effects, the size of these effects is difficult to pin down from existing empirical research.

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. [Bergman, 1990](#); [Conrad and Schröder, 1993](#); [Beauséjour et al., 1995](#); [Lee and Roland-Holst, 1997](#); and [Goulder, 1995](#); [Conrad, 1999](#) provides a review). There are, also, 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 since they allow the system-wide effects of the energy efficiency improvement to be captured. Recall that these comprise (i) a need to use less physical energy inputs 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 relatively energy-intensive products benefit 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 real household incomes rise.

[Allan et al. \(2007a\)](#), examines such effects in the context of an improvement in efficiency in the industrial use of energy in the UK economy. Here we turn our attention to the case of a single region of the UK using AMOSENVI, a CGE modelling framework parameterised on data from Scotland.² This single region analysis is made particularly interesting because of the extent of Scottish trade in electricity with the rest of the UK.

3.1. General structure

This section provides a brief description of the general model framework. A more formal description is given in Appendix 1. AMOSENVI has 3 transactor groups, namely households, corporations, and government³; 25 commodities and activities, 5 of which are energy commodities/supply (see [Fig. 1](#) and Appendix 2 for details); and two exogenous external transactors, the Rest of the UK (RUK) and the Rest of the World (ROW).

² AMOS is an acronym for a macro–micro model of Scotland. AMOSENVI is a model variant with an appropriate sectoral disaggregation and a set of linked pollution coefficients, developed specifically to allow the investigation of environmental impacts.

³ 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.

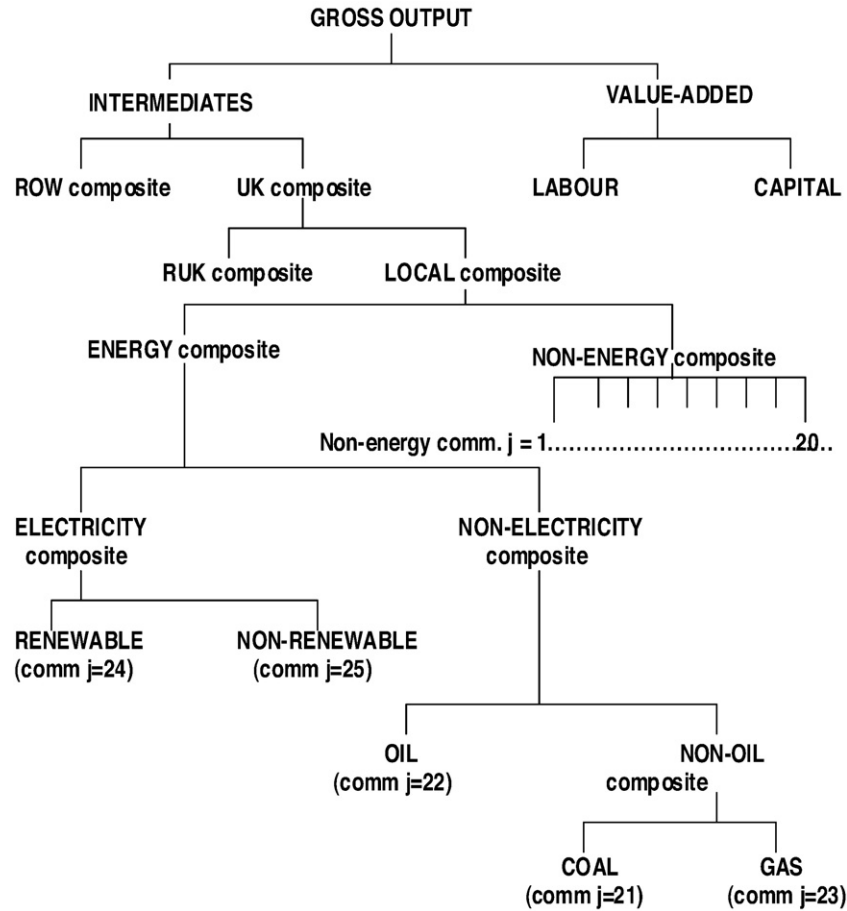


Fig. 1 – Production structure of each sector in the 25 sector/commodity AMOSENVI KLEM framework.

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, generally of a CES form but with Leontief and Cobb–Douglas being available as special cases (see Fig. 1). 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 the demand for Scottish exports and imports is sensitive to changes in relative prices between (endogenous) Scottish and (exogenous) RUK and ROW 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 regionally-bargained real wage function in which the regional real consumption (post-tax take-home) wage is directly related to workers' bargaining

power and therefore inversely related 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):

$$w_{s,t} = \alpha - 0.068u_s + 0.40w_{s,t-1} \quad (8)$$

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.⁴ 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

⁴ Parameter α is calibrated so as to replicate the base period, as is β in Eq. (9). These calibrated parameters play no part in determining the sensitivity of the endogenous variables to exogenous disturbances but the initial assumption of equilibrium implied by the calibration procedure is an important assumption.

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. The desired capital stock is determined on cost-minimisation criteria and the actual stock reflects last period's stock, 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

Where endogenous 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 between Scotland and RUK, 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:

$$m = \beta - 0.08(u_s - u_r) + 0.06(w_s - w_r) \quad (9)$$

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 RUK real consumption wage and unemployment rates, respectively, and β is a calibrated parameter. In the multi-period 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.

3.2. Treatment of energy inputs to production in AMOSENVI

Fig. 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 consensus 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 adopted here (e.g. Beauséjour et al., 1995).⁶

In the simulations reported in this paper, in each sector Leontief functions are specified at two levels of the hierarchy – 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.

3.3. 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 Fig. 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.⁷ Both the input-pollution coefficients attached to energy imports and to locally-supplied energy inputs are determined using data on the CO₂ emissions intensity of different types of fuel use in the

⁶ Note that there is also a 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). To avoid this problem, Hertel and Mount (1985), Despotakis and Fisher (1988) and Li and 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 as 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 and Mount (1985), Despotakis and Fisher (1988) and Li and Rose (1995) all choose to employ two-levels cost functions, with substitution between KLEM inputs on the first level, then within the energy and/or material aggregates on the second level. Thus, even these authors are in fact prepared to accept some separability assumptions.

⁷ 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. We have (experimental) information (supplied by the Scottish Government IO team) on the commodity composition of imports in each production sector and each category of demand. The commodity composition (including energy commodities) of imports differs between sectors and demand category and is different for RUK and ROW. However, in our analysis, the base year commodity composition of each composite import good to each user is assumed fixed (we model a composite commodity imported from each exogenous external transactor, e.g. in Fig. 1). This implies that there is a fixed relationship between imports from each external source (RUK and ROW) to each production sector and final consumption group, and the direct emissions generated from the use of these imports.

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.

UK economy. The application of fuel-use emissions factors is fairly straightforward in the case of CO₂ emissions, which 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 tend to focus solely or primarily on CO₂ emissions (see Turner, 2002, for a review).

However, modelling input-pollution relationships becomes more complex for non-CO₂ emissions. This is because non-CO₂ emissions generally depend not only on fuel type, but also on combustion conditions and technology, meaning that appropriate emissions factors are likely to be more difficult to identify and too numerous for models with a high level of sectoral detail. Thus, at present 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 (Eq. 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. Here, in the case of CO₂ emissions we identify industrial process emissions relating to the production of mineral products and metal in the '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 linked 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, which may be beneficial in terms of UK and global sustainability if Scotland is capable of producing electricity using less polluting technology.⁸ In our base year of 1999, around 12% of Scottish electricity production is 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 results presented in this study.

3.4. Database

The sectoral breakdown of the 1999 Social Accounting Matrix (SAM) for Scotland 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.¹⁰ We also draw 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 Fig. 1 and Appendix 2). However, the database is still limited in that the electricity sector is reported as a vertically integrated sector in the I-O accounts, thereby combining generation, distribution and supply activities.¹¹ When the sector is disaggregated by generation type to identify the 'Renewable' and 'Non-Renewable' sectors, these sectors remain vertically integrated.¹²

No appropriate Scottish data on sectoral emissions and physical fuel use are available. However, some regional specificity is introduced to the environmental (CO₂ and fuel use) database for Scotland using the following sources. For Scottish produced energy we have used the I-O data on the sectoral destination of outputs from the local energy supply sectors and for imported fuels we have drawn on experimental data provided by the I-O team at the Scottish Executive that break sectoral imports down by commodities. The following method is used.¹³ First, UK data on physical fuel intensities for the broad (directly polluting) fuel types – oil, gas and coal – are employed 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. 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, each sector's estimated emissions from each type of fuel use are divided 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 £1 million expenditure on each local and imported fuel respectively). See Eq. (22) in Appendix 1.

To generate the output-pollution coefficients for non-fuel-combustion emissions of CO₂ in the '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.

3.5. Rebound, backfire and sustainability indicators in AMOSENVI

The indicators we incorporate within AMOSENVI reflect those 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

⁸ Imports of electricity to Scotland from RUK correspond to just under 10% of Scottish exports of electricity to RUK.

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 The Social Accounting Matrix was constructed around the 1999 Scottish Input Output Tables, which are provided by the Scottish Government (Scottish Executive, 2002a) and are available at <http://www.scotland.gov.uk/Topics/Statistics/Browse/Economy/Input-Output>.

¹¹ This sector is classed as IOC 85, mapping to activity 40.1 in the Standard Industrial Classification, SIC.

¹² 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 Allan et al. (2007b).

¹³ A more detailed account is given in Turner (2003).

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 \(2002b, 2003\)](#) that focus on the sustainability of energy consumption and production¹⁴, we identify:

- Scottish energy consumption
 - Total use of electricity (gigawatt hours)
 - Total use of non-electricity energy (tonnes of oil equivalents)
- Share of electricity generated in Scotland using renewable sources (share of total electricity output, in gigawatt hours, from the renewable source sectors).¹⁵

The broad target for the consumption of both electricity and non-electricity energy should decline. Of course, this will happen in response to an energy efficiency enhancement, provided that there is no backfire. However, the extent of rebound (and possible backfire) can be calculated by comparing the scale of any reduction (increase) in energy consumption with the scale of the efficiency stimulus. There is an additional 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.

The main indicator of resource productivity recommended for the UK (see [Pearce, 2001](#)) is the ratio of GDP (Y) per unit of energy (E), where a rise in this ratio indicates an improvement in the sustainability of economic development. Partly due to the problem of differing units of measurement, our model incorporates two variants of this indicator:

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

We report these sustainability indicators in our results. GDP is expected to increase in response to the stimulus to energy efficiency, given the effective reduction in the relative price of energy. Therefore with rebound, these “relative” indicators of sustainability (Y/E (1) and Y/E (2)) will increase. However, even under backfire, Y/E would be expected to rise in response to an energy efficiency stimulus as long as the proportionate increase in GDP is greater than the proportionate increase in energy use. 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 the achievement of Kyoto targets.

The UK government also tracks the “carbon intensity” of the UK economy, defined as the ratio of GDP (Y) per unit of CO₂ emissions (P). Again, a rise in this ratio is interpreted as an

improvement in the sustainability of economic development. 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 backfire as improving sustainability as long as output is stimulated by proportionately more than CO₂ emissions. 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 from simulations of a 5% exogenous 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.¹⁶ Intermediate inputs account for 73% of Scottish demand for electricity and 48% of the demand for non-electricity energy which are the corresponding values for α when Eq. (7) is used to calculate rebound effects. The resulting changes in key energy and economic variables 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 in each period. 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.

4.1. 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 simulations comply with these expectations. 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](#).¹⁷

¹⁴ These are indicators 12 and 13 in [Scottish Executive \(2002b, 2003\)](#).

¹⁵ As noted above, we use extended experimental data provided by the I-O branch of the Scottish Executive to disaggregate the Electricity sector in the Scottish I-O tables for 1999. The renewable source sectors identified in these data are hydro and wind. The non-renewable source sectors are coal, gas and nuclear.

¹⁶ That is to say, in each industry there is a 5% increase in the efficiency with which the energy composite combines with the non-energy composite to produce the local composite input (see [Fig. 1](#)).

¹⁷ These are conceptual time periods. However, the short and long-run results can be related directly to the period-by-period simulations reported later in this section. The short-run results correspond to those in period one: the long-run results are those that the model approaches when it is run over a large number of time periods with migration and investment endogenous. The medium-run results correspond to running the period-by-period model over a large number of time periods with migration endogenous but capital stocks fixed. We do not perform such period-by-period simulations in this paper.

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 (%)	63.2	64.2	131.6
Total non-electricity energy consumption	–1.08	–1.05	0.81
Non-electricity energy rebound effect (%)	54.4	55.5	134.1

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 an increase in 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 increase 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).

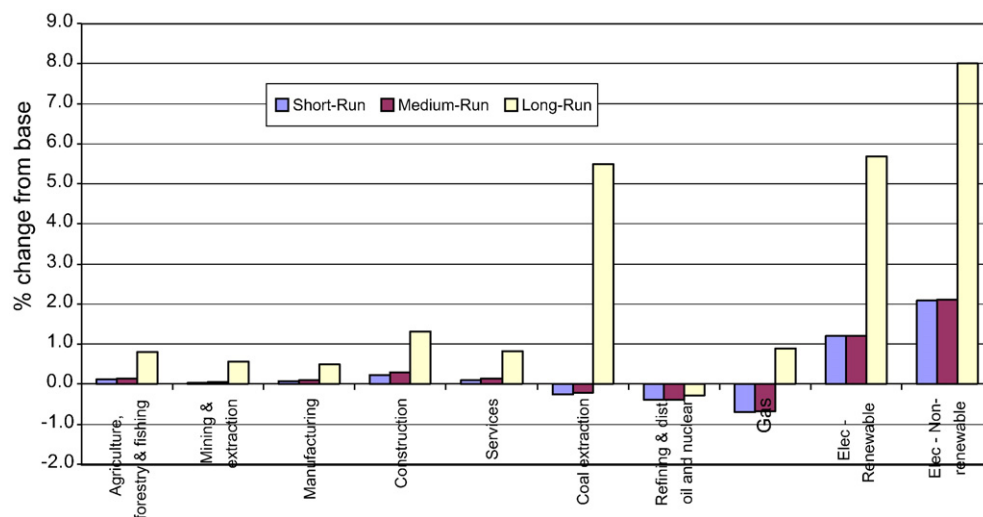
In principle, the ability to substitute in favour of the intermediate composite (which includes energy inputs) and away from value-added (labour and capital inputs) at the top

level of the production hierarchy in each industry could frustrate the expected labour market effects. However, with the default parameter values, the substitution possibilities are limited and in practice are dominated by the output effect. Immigration ensures that real wages and the unemployment rate 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 54% for electricity and non-electricity energy respectively. In the long-run energy demands actually increase, so that backfire is present (a rebound effect of 132% in electricity and 134% in other energy consumption). While energy efficiency does initially lower the demand for energy, the increase in competitiveness is concentrated in the most energy-intensive sectors of the economy. Where these sectors are also exporters, this generates a large boost to that sector and to the economy as a whole.

The changes in the outputs of aggregated non-energy sectoral groups and the five individual energy sectors are reported in Fig. 2. Short, medium and long-run results are given. The increase in efficiency, and consequent improvement in competitiveness, leads to positive output effects in all the non-energy aggregated sectors, although the stimulus to the real wage has a countervailing influence in the short-run. For the energy sectors, however, the situation is a little more complex.

For all the non-electricity energy supply sectors, there are negative output effects, at least in the short and medium run, due to the fall in intermediate demand as energy productivity increases. This is also combined with the negative competitiveness effect as the real wage increases. However, output in

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

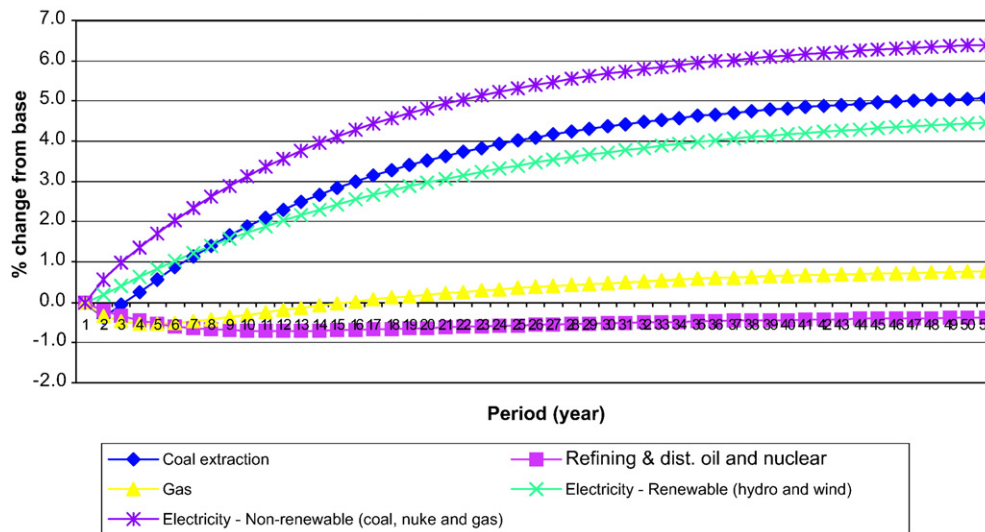


Fig. 3 – Change in sectoral value-added in Scottish energy sectors in response to a 5% increase in energy efficiency in all production sectors.

the electricity sectors rises, even in the short-run. This is because in 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). This demand effect is driven by two key characteristics of Scottish electricity production. First, it is very energy intensive — 26% and 29% of the input requirements of the renewable and non-renewable electricity sectors respectively.¹⁸ 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. Second, there is a large stimulus to export demand as the price of Scottish electricity falls relative to electricity produced elsewhere in the UK.

Fig. 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 expected given that both demand and supply elasticities tend to increase through time as capital stocks (and population) adjust. (The results in Fig. 3 suggest, 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.

¹⁸ Recall that these are vertically integrated sectors, incorporating all production and distribution activities. In the case of the renewable sector, energy is an important input to distribution activities, according to the experimental Scottish I-O data used to identify these sectors.

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 to the capital stock in the non-renewable electricity generation sector. However, it might be useful in future research to examine the impacts of introducing constraints on investment, particularly for coal-fired power stations, of which only three remain in Scotland.

The impacts on the sustainability indicators identified in Section 3 are striking. First, the growth in both energy consumption in Scotland can be seen in Fig. 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 in period 16, one period later.

Second, another energy indicator given in Section 3 is the share of electricity generated from renewable sources. Fig. 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. An improvement in energy efficiency therefore causes a perverse change in a key sustainability indicator.

Third, Fig. 4 shows the impact of the energy efficiency shock on the energy productivity indicators for the electricity, Y/E (1), and non-electricity energy consumption, Y/E (2), as a share of Scottish GDP. Typically, a rise in the value of these ratios would be taken as a move in the direction of more sustainable development. However, Fig. 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. Both measures ultimately fall below their base year values. These phenomena can, of course, only arise in the presence of significant backfire.

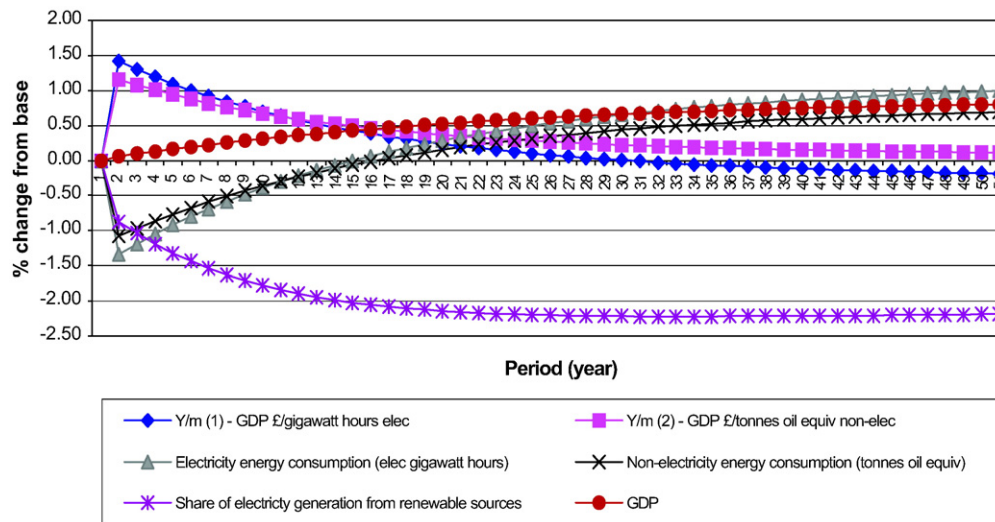


Fig. 4 – Impact of a 5% increase in energy efficiency in all production sectors on energy indicator variables.

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 Fig. 5).

In summary, our results suggest that an improvement in energy efficiency in a single, open regional economy can generate a stimulus to energy production and consumption and a deterioration in environmental indicators. As Fig. 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, while backfire occurs in the longer term as energy consumption actually increases above the baseline.

4.2. Sensitivity analysis around central case scenario

Our theoretical analysis identifies a number of key parameters that are likely to govern the extent of rebound/backfire: elasticities of substitution of energy for other inputs in production; price elasticities of demand for outputs; the elasticities of supply of other factors; and 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 supply of other factors given that these elasticities change directly with the 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 groups of sectors we can infer the impact of sectoral 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 model closures.

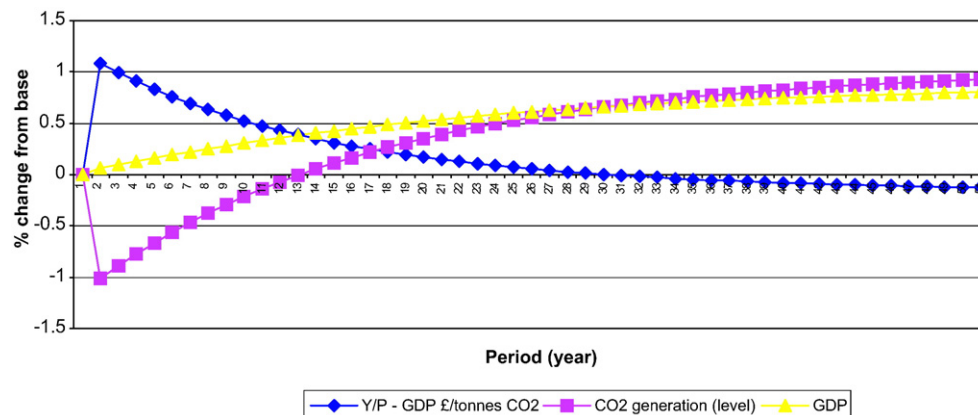


Fig. 5 – Impact of a 5% increase in energy efficiency in all production sectors on environmental indicator variables.

4.3. Varying key substitution elasticities in the production function

On the basis of our theoretical discussion, the parameters that would be expected 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 Fig. 1), SIGMAL, which is the parameter whose value we vary in Table 2, and between value-added and intermediate inputs to determine gross output, SIGMAD, the parameter that we vary in Table 3. 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. Recall that over this time interval 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, SIGMAL. 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. The structure of the production functions embedded in AMOSENVI is rather more complex than the case considered by Saunders (e.g. 2000a,b, in press) and our results reflect the consequences of a full general equilibrium model. However, it is instructive to note that all of the results in Table 2 exhibit backfire, even for the very low substitution elasticity 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 of substitution: total electricity consumption increases by just over 0.47% in the low, as against over 2.51% in the high elasticity case. The high elasticity simulation produces an electricity rebound effect of 169.3%, while with

Table 2 – Long-run 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)	0.880	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	1.15	2.514
Electricity rebound effect (%)	113.0	131.6	169.3
Total non-electricity energy consumption	0.337	0.81	1.756
Non-electricity energy rebound effect (%)	114.2	134.1	174.2

Table 3 – Long-run impact of changing 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)	0.893	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	1.01	1.15	1.43
Electricity rebound effect (%)	127.8	131.6	139.3
Total non-electricity energy consumption	0.69	0.81	1.04
Non-electricity energy rebound effect (%)	129.2	134.1	143.8

the low elasticity 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 174% and 114% respectively.

Table 3 shows the long-run results from varying the elasticity of substitution between value-added and intermediate inputs, SIGMAD. This is the point at the very top level of the production hierarchy used in AMOSENVI (see Fig. 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. This means that in our production hierarchy the value of SIGMAD 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.

4.4. 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 world (ROW) and rest of the UK (RUK) respectively (the RHOW and RHOUK parameters in Tables 4 and 5 respectively). These parameters 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).

Table 4 – Long-run impact of changing the ROW export demand elasticities (the RHOW parameters) (percentage changes from base year)

	E=5	E=2	E=5	E=5
	O=2	O=2	O=5	O=5
	N=2	N=2	N=2	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	1.15	1.148	1.148	1.288
Electricity rebound effect (%)	131.6	131.6	131.6	135.5
Total non-electricity energy consumption	0.81	0.806	0.807	0.949
Non-electricity energy rebound effect (%)	134.1	134.1	134.1	140.1

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 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, reported in Table 4,

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 results given in Table 5 that apply to the RUK case. 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" exports 51%, and the two electricity sectors export 31%. The increases in GDP range from 0.61% with all RUK export demand elasticities set at 2, to 1.09% with all elasticities at 5.

The variation is also large for both electricity and non-electricity total energy consumption. Crucially, the impact on overall energy consumption varies significantly with the RUK export demand elasticities. For low elasticities both electricity and non-electricity energy consumption fall. The change in consumption is –0.65%, for electricity and –0.78% for non-electricity. Where the export demand elasticities are high there are increases in electricity and non-electricity energy consumption of 1.32% and 1.00% respectively. Where a decrease in energy consumption occurs there is no backfire, though there are still very large rebound effects (relative to the findings of other studies) of 82.2% for electricity consumption and 67.2% for non-electricity consumption.

Recall that the responsiveness of output demands to relative prices does not feature at all in Saunders (2000a,b, in press) 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 is important in governing the scale of rebound and backfire effects, a result

Table 5 – Long-run impact of changing the RUK export demand elasticities (the RHOUK parameters) (percentage changes from base year)

	E=5	E=2	E=5	E=5
	O=2	O=2	O=5	O=5
	N=2	N=2	N=2	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	1.15	–0.648	1.153	1.318
Electricity rebound effect (%)	131.6	82.1	131.8	136.3
Total non-electricity energy consumption	0.81	–0.777	0.814	0.998
Non-electricity energy rebound effect (%)	134.1	67.2	134.4	142.2

Table 6 – Long-run impact of changing the specification of the labour market (percentage changes from base year)

	Regional wage	National wage
	Bargaining	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	1.15	0.860
Electricity rebound effect (%)	131.6	123.7
Total non-electricity energy consumption	0.81	0.588
Non-electricity energy rebound effect (%)	134.1	124.9

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	2.34	–1.21	–0.05	–0.01	–0.04
Electricity rebound effect (%)	131.6	249.5	41.4	52.3	72.0	45.6
Total non-electricity energy consumption	0.81	1.60	–0.82	–0.17	–0.03	–0.14
Non-electricity energy rebound effect (%)	134.1	243.8	34.8	40.3	54.4	35.6

which emphasises the importance of our extensions to Saunders' theoretical analyses.

4.5. 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 under a national bargaining system. With national bargaining, the region effectively becomes a nominal wage-taker, which generates significant variation in all the key macroeconomic results. This reflects the more limited expansion under national bargaining in response to the positive supply-side shock: under national bargaining the nominal wage is invariant to the fall in Scottish prices, so that real wages rise. The more limited expansion in economic activity inhibits the rise in both electricity and non-electricity energy consumption, and the consequent backfire effects are less pronounced. However, the changes to the central case result on the degree of backfire are small for both electricity and non-electricity energy.

4.6. Varying the sectors targeted with the energy efficiency shock¹⁹

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. Column 2 gives the results where the shock is directed at the 5 energy supply sectors, that is sectors 21–25, and column 3 where only the non-energy sectors are shocked, sectors 1–20.²⁰ The results in columns 2 and 3 in Table 7 therefore sum approximately to those in column 1.²¹

Where the increase in energy efficiency is limited to the energy supply sectors, the effects on the key macroeconomic variables are smaller than where the efficiency gain applies across all the production sectors in the economy: for these variables, the values in column 2 are therefore smaller than corresponding values in column 1. However, the increases in both electricity and non-electricity energy consumption are greater where the efficiency gain is restricted to production in the energy sectors, so that the backfire effects are appreciably larger than in the base case.²² This is primarily due to activity in the electricity sectors. This can be verified by considering the figures given in column 5, where the efficiency shock is targeted at the “Oil” and “Gas” supply sectors. Here we observe a slight drop in electricity and non-electricity energy consumption and there is no backfire effect (although there are still significant rebound effects). Column 3 shows the results of an increase in efficiency directed at the twenty non-energy supply sectors. Again, the effects on the key

²⁰ The sectors are listed in Appendix 2.

²¹ This is, apart from the rebound effects where the figure in column 1 is the weighted sum of the figures in columns 2 and 3.

²² Recall that the backfire effects are calculated as a proportion of the energy use in those sectors that received the efficiency gain. However, the energy change results given in all the cases reported in Table 7 are proportionate changes in total energy use.

¹⁹ We are indebted to an anonymous referee for suggesting this element of the sensitivity analysis.

macroeconomic variables are smaller than in column 1 due to the more limited shock. However, in this case there is a decrease in both electricity and non-electricity energy consumption at the aggregate level, though with sizeable rebound effects.

The presence and magnitude of the economy-wide rebound and backfire effects does not depend only on the energy intensity of production. We shock separately the most electricity-intensive production sector – Sector 9, ‘Chemicals etc’ – and the least electricity-intensive production sector – Sector 3, ‘Sea Fishing’. We do not present the full results of these two shocks as the macroeconomic effects are negligible in the presence of such small disturbances. We simply focus on the energy consumption effects.

For Sector 9, the long-run decrease in aggregate electricity energy consumption is smaller than when all 20 non-energy sectors are shocked (–0.05% compared to –1.21% in column 3 of Table 7) and the electricity rebound effect is larger (54.6% as against 41.4%). However, if we shock Sector 3, the least electricity-intensive sector, while electricity consumption in the sector itself falls, there is a small increase in aggregate electricity consumption of 0.0008%. This is mainly driven by increases in imported and domestic electricity used by the ‘Transport’ and ‘Textiles and Clothing’ sectors, both of which are direct intermediate suppliers of inputs to the ‘Sea Fishing’ sector. The increase in aggregate energy consumption is small but the efficiency shock is applied to a small share of total energy use. This means that there is in fact a sizeable backfire effect in terms of electricity consumption (323.2%) even though the shock is limited to the least (directly) electricity-intensive production sector in the economy. This demonstrates why a general equilibrium framework is essential in 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 takes place only 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 efficiency improvement is introduced to all five sectors in the economy that are heavier users of gas and oil than of electricity. These are sectors 2, 3, 16, 22 and 23. Then in columns 5 and 6 respectively we split these into energy supply and non-energy supply sectors. Backfire does not occur in any of these cases for either electricity or non-electricity energy consumption, although significant rebound effects still apply with the rebound effect markedly higher for electricity, as against non-electricity, energy use.

5. Conclusions

In this paper we explore the impact of improvements in energy efficiency both theoretically and empirically using a flexible, energy–economy–environment CGE framework. We argue that predicting the environmental impacts of significant improvements in energy efficiency requires such a general equilibrium approach. This is because improvements in energy efficiency generate important sys-

tem-wide output and substitution effects that tend to increase energy use, and act as countervailing influences to the direct effects of being able to “produce more with less”.

We seek to clarify the theoretical literature on rebound and backfire effects that questions the value of energy efficiency enhancement in reducing energy consumption. In particular, we show that Saunders’ (2000a,b) theoretical analyses require augmentation in an open-economy context and emphasise the importance of the time interval under consideration. We argue that zero rebound, at the macro level, is highly unlikely, so that the key question is then purely empirical: how much rebound will occur 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 that gradually increases through time, eventually resulting in backfire in terms of electricity consumption: for electricity production, however, backfire is immediately apparent.

These results are not what advocates of energy efficiency would anticipate or wish for, but they are important for the appropriate conduct of energy policy. We identify the impact of improvements in energy efficiency on a number of key sustainability indicators used by the UK and Scottish governments. These include the ratios of GDP to energy use and to CO₂ emissions. Again, in this case backfire sends both of these indicators in the wrong direction. Saunders (2000a,b) gives overwhelming importance to the elasticity of substitution in production between energy and other inputs in determining the degree of rebound. However, our sensitivity analysis shows that this is unduly restrictive: both rebound and backfire can occur even when this elasticity is very low (though these size of these effects is increasing in the value of the elasticity of substitution).

The results presented here imply that in order to ensure that increased energy efficiency generates improvements in local sustainability indicators it is necessary to counteract the positive competitiveness effects that occur due to the fall in the cost of production in energy-intensive sectors. This could be achieved by the introduction of a (higher) tax on energy use or a carbon tax.

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. Backfire would be much less likely if the energy efficiency increase were to be mandated throughout the UK.²³

²³ 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). For an example of a UK interregional Input-Output analysis see McGregor et al. (2008).

Second, 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. But this may come at the expense of worsening Scottish air quality due, say, to higher PM10 emissions. This suggests a possible trade-off between local and global environmental concerns resulting from improvements in energy productivity.

Third, 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 increased autonomy at the regional level in the presence of interregional environmental spillovers.

Fourth, the message for sustainability depends on the information content of the indicators used here: while 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, although some commentators argue that such economic indicators are themselves deficient (Pezzey et al., 2006).

We believe that the key point that this paper makes is an important one: focussing on improvements in energy efficiency 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 Bruvold 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 do not regard our analysis as totally undermining policies designed to enhance energy efficiency. Rather, it serves to emphasise that such policies cannot, in general, be relied upon in isolation 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 on 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. In this sense we would fully endorse Birol and Kepler's (2000) view that policies concerning technology and relative prices 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	$p q_i = p q_i (p v_i, p m_i)$
(2) Value-added price	$p v_i = p v_i (w_n, w_{k,i})$
(3) Intermediate composite price	$p m_i = p m_i (p q)$
(4) Wage setting	$w_n = w_n (\frac{N}{L}, c p_i, t_n)$
(5) Labour force	$L = \bar{L}$
(6) Consumer price index	$c p_i = \sum_i \theta_i p q_i + \sum_i \theta_i^{RUK-RUK} p q_i$ $+ \sum_i \theta_i^{ROW-ROW} p q_i$
(7) Capital supply	$K_i^S = \bar{K}_i^S$
(8) Capital price index	$k p_i = \sum_i \gamma_i p q_i + \sum_i \gamma_i^{RUK-RUK} p q_i$ $+ \sum_i \gamma_i^{ROW-ROW} p q_i$
(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	$Y = \psi_n N w_n (1 - t_n) + \psi_k \sum_i w_{k,i} (1 - t_k) + \bar{T}$

Appendix 1 (continued)

Equations	Short-run
(14) Commodity demand	$Q_i = C_i + I_i + G_i + X_i + R_i$
(15) Consumption demand	$C_i = C_i(pq_i, \bar{p}q_i^{RUK}, \bar{p}q_i^{ROW}, Y, cpi)$
(16) Investment demand	$I_i = I_i(pq_i, \bar{p}q_i^{RUK}, \bar{p}q_i^{ROW}, \sum_i b_{ij}I_j^d)$ $I_j^d = h_j(K_j^d - K_j)$
(17) Government demand	$G_i = \bar{G}_i$
(18) Export demand	$X_i = X_i(p_i, \bar{p}_i^{RUK}, \bar{p}_i^{ROW}, \bar{D}^{RUK}, \bar{D}^{ROW})$
(19) Intermediate demand	$R_{ij}^d = R_i^d(pq_i, pm_j, M_j)$ $R_i^d = \sum_j R_{ij}^d$
(20) Intermediate composite demand	$M_i = M_i(pv_i, pm_i, Q_i)$
(21) Value-added demand	$V_i = V_i(pv_i, pm_i, Q_i)$
(22) Pollutants (CO ₂)	$POL_{CO_2} = \sum_i [e_{if}f_{if} + (g_i \cdot K_i) + h_i] Q_i$
Multi-period model	Stock updating 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	$K_{i,t} = (1-d_i)K_{i,t-1} + I_{i,t-1}^d$

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
t_n, t_k	average direct tax on labour and capital income
u	unemployment rate
W_n, W_k	price of labour to the firm, capital rental
Ψ	share of factor income retained in region
θ	consumption weights
γ	capital weights
POL_k	quantity of pollutant k (output-pollution approach)
POL_{CO_2}	quantity of CO ₂
ϕ_{ik}	output-pollution coefficients
e_{ij}	fuel-use emissions factors
f_{ij}	fuel purchases
g_i	import emissions factors
κ_i	import purchases
δ_i	process output-pollution coefficients

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

$pm(\cdot), pq(\cdot), pv(\cdot)$	CES cost function
$k^s(\cdot), w(\cdot)$	Factor supply or wage-setting equations
$K^d(\cdot), N^d(\cdot), R^d(\cdot)$	CES input demand functions
$C(\cdot), I(\cdot), X(\cdot)$	Armington consumption, investment and export demand functions, homogeneous 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

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 and distr oil and nuclear) 35
23	Gas 86
	Electricity
24	Renewable (hydro and wind) 85
25	Non-renewable (coal, nuke and gas)

Appendix 3. CO₂ pollution coefficients for Scotland in 1999

Polluting sector/final demand category	Tonnes energy-related CO ₂ per £1 million purchases of					Tonnes CO ₂ CO ₂ (non-energy) per £1 million total output
	Local coal	Local oilbased fuels	Local gas	Imports from RUK	Imports from ROW	
Agriculture	51,719	23,188	22,282	284	100	0
Forestry planting and logging	51,719	24,194	22,282	939	518	0
Sea fishing	51,719	23,279	22,282	311	5513	0
Fish farming	51,719	23,279	22,282	0	0	0
Other mining and quarrying	52,317	23,228	22,282	55	302	0
Oil and gas extraction	52,317	23,267	27,692	770	3691	187
Mfr food, drink and tobacco	52,559	23,327	22,282	185	9	0
Mfr textiles and clothing	52,559	23,290	22,282	43	10	0
Mfr chemicals etc	52,559	23,271	21,512	152	0	0
Mfr metal and non-metal goods	55,484	22,724	22,282	152	1	118
Mfr transport and other machinery, electrical and inst eng	52,559	23,139	22,282	41	1	0
Other manufacturing	52,559	23,259	22,282	478	0	0
Water	52,317	22,895	22,282	209	453	0
Construction	52,317	23,146	22,282	138	6	0
Distribution	52,317	23,007	22,282	938	17	0
Transport	52,317	19,127	22,282	2132	127	0
Communications, finance and business	52,317	22,941	22,282	130	788	0
R&D	52,317	22,758	22,282	0	0	0
Education	50,840	23,173	22,282	984	80	0
Public and other services	50,866	23,254	22,282	352	624	0
Coal (extraction)	0	26,923	22,282	5	0	0
Oil (refining and distribution, nuclear)	17,160	21,354	22,282	0	0	310
Gas	52,317	1349	22,282	128	0	0
Electricity — renewable (hydro and wind)	51,466	22,933	22,282	1323	0	0
Electricity — non-renewable (coal, nuke and gas)	51,466	4910	22,282	6147	0	0
Households	49,633	22,672	22,282	248	142	0
Tourists	49,633	22,672	22,282	113	338	0

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