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Karen Turner

Nick Hanley

Stirling Economics Discussion Paper 2010-17

December 2010

Online at http://www.economics.stir.ac.uk

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Karen Turner* and Nick Hanley

Division of Economics, Stirling Management School, University of Stirling

* Corresponding author

Acknowledgements

The research reported in this paper is supported by the UK Economic and Social Research Council under the First Grants Initiative (ESRC grant ref: RES-061-25-0010). We are grateful to participants at the annual conference of the European Association of Environmental and Resource Economists (EAERE) in Amsterdam, June 2009, and seminars at the University of Aberdeen and ETH (Zurich) for helpful comments and on an earlier version of this paper. We also gratefully acknowledge the comments of two anonymous reviewers on the initial submission of this paper to Energy Economics. Finally, we are grateful to Janine De Fence for research assistance in the empirical work reported.

Abstract

Technological change is one factor used to justify the existence of an Environmental Kuznets Curve, and technological improvements have been argued to be a key factor in mitigating the impacts of economic growth on environmental quality. In this paper we use a CGE model of the Scottish economy to consider the factors influencing the impacts of one form of technological change - improvements in energy efficiency - on absolute levels of CO_2 emissions, on the carbon intensity of the economy (CO_2 emissions relative to real GDP), and the per capita EKC relationship. These factors include the elasticity of substitution between energy and non-energy inputs, responses in the labour market and the structure of the economy. Our results demonstrate the key role played by the general equilibrium price elasticity of demand for energy, and the relative influence of different factors on this parameter.

Keywords: computable general equilibrium models; technical progress; energy efficiency; rebound effects; Environmental Kuznets Curve

JEL Q40, Q54, Q56,

Energy Efficiency, Rebound Effects and the Environmental Kuznets Curve.

1. Introduction.

The Environmental Kuznets Curve (EKC) has emerged as both an empirical phenomenon and as a political message. The empirical phenomenon – much debated – is that rising prosperity will eventually be accompanied by falling pollution levels, following from some earlier growth period where both prosperity and pollution are increasing (Deacon and Norman, 2006; Markandya et al, 2006; Johansson and Kristrom, 2007). The political message of the EKC curve is that promoting economic growth does not have to be seen as being in conflict with a cleaner environment, and indeed that growth can eventually be associated with falling levels of pollution, if suitable policies are put in place. However, recent econometric findings cast doubt on the simple EKC story that growth eventually results in falling pollution, at least for certain pollutants such as CO2 (Vollebergh et al, 2009).

The standard theoretical argument for why pollution levels can fall as GDP per capita rises past some turning point relies on a combination of three factors (Jaffe et al, 2003) The first is structural change in the economy, involving a move away from an industrial base with high levels of pollution per unit of value-added, towards an economy increasingly dominated by cleaner industries and the service sector. The second argument is that as income rises, the demand for environmental quality increases at a more-than-proportional rate due to the income elasticity of Willingness To Pay being greater than one (although see Hokby and Soderquist, 2003, and Jacobsen and Hanley, 2008). This translates into political pressure for tougher environmental policy instruments, which drives down the level of pollution per unit of GDP (Bruvoll et al, 2003). The third consideration, which this paper focuses on, is that technological improvements reduce the burden of economic activity on the environment, in terms of lower emissions per unit of GDP. For example, cars are produced with improved fuel efficiency standards; houses are built with more energy-efficient materials; production processes improve the efficiency with which raw materials are transformed into consumer goods.

Promoting technological progress can thus be seen as a means of reducing the environmental burdens of economic activity. A specific example relates to climate change and energy efficiency. The UK government has placed improvements to energy efficiency as a key element of climate policy in terms of achieving reductions in CO2 emissions over time (UK Climate Change Committee, 2008).

However, the actual impact of increased energy efficiency on total energy use and CO_2 emissions is uncertain due to the phenomenon of 'rebound' effects (Jevons, 1865; Khazzoom 1980; Brookes 1990; Herring, 1999; Birol and Keppler, 2000; Saunders, 1992, 2000a,b; Schipper, 2000). Policy concern in the UK regarding energy efficiency and rebound effects was raised in a report from the House of Lords (2005). A relevant question is thus the extent to which improvements in energy efficiency translate into improvements in both the level of absolute emissions and the ratio of GDP to CO_2 emissions at the level of the economy as a whole. This is the question that this paper is concerned with. We are also interested in understanding the relative importance of factors which might determine the extent to which an economy "moves along" its EKC in response to an energy efficiency improvement. The factors focussed on are: (i) the time period under consideration; (ii) the elasticity of substitution of energy for other inputs; (iii) responses in the labour market; (iv) which sectors directly benefit from the technological change; and (v) the structure of the economy.

2. Literature Review

The first papers on the EKC were by Grossman and Krueger (e.g., 1994) who used reduced form regression models to show that, for most pollutants, a country will move along this U shaped curve as it becomes richer. More recent empirical contributions include overviews by Deacon and Norman (2006), and findings for biodiversity (McPherson and Nieswiadomy, 2005)) and for CO_2 (Dijkgraff and Vollebergh, 2005; Vollebergh et al, 2009). A number of authors have presented theoretical models which aim to explain the EKC (see, for example, Lopez, 1994; Stokey, 1998; Andreoni and Levinson, 1998; Selden and Song, 1995). This literature identifies three main reasons for movement along for the EKC: composition and structural changes in the economy, improvements in environmental regulation due to rising demand for environmental quality linked to income increases, and technological change. The standard hypothesis with respect to technological progress suggests that as a country becomes wealthier it can afford to spend more on research and development which can lead to more advanced and environmentally-friendly production techniques. Increasing returns to abatement technology can also generate an inverted U-shape (Andreoni and Levinson, 1998; Pasche, 2002).

Evidence on the link between economic growth, technological change and pollution is supported by Anderson and Cavendish (2001), who use a dynamic simulation model to look at PM, SO_2 and CO_2 trends in developing countries. Empirical evidence against technological improvements as a driver of improved environmental quality is presented by Lantz and Feng (2005), who show that during the period between 1970 and 2000, Canada showed a U shaped curve (not an inverted U shape) for the relationship between CO_2 and technology. Nonetheless, many other contributors do support the argument that technological progress has a positive impact – see, for example, Pizer and Popp (2008) who argue that technological progress will be key in the long run to reduce GHG emissions. Johansson and Kristrom (2007) find exogenous technological progress to be an important driver of movements along an EKC for sulphur dioxide in Sweden.

In earlier papers (Allan et al, 2007; Anson and Turner, 2009; Hanley et al, 2006, 2009; Turner, 2008, 2009), we have shown that exogenous improvements in energy efficiency are likely to produce economy-wide rebound or backfire effects that partially or wholly offset energy savings from these pure efficiency improvements. This finding is consistent with a growing literature on rebound and backfire effects (see Sorrell, 2007, for a recent review). In our previous work we argue that the occurrence of such rebound effects is due to a combination of general equilibrium effects, all linked to the overall (general equilibrium) price elasticity of demand for energy. As energy becomes more productive, its effective price falls – less energy units must be purchased to produce a given amount of work. This increases energy use through a substitution effect with other inputs to production. Moreover, the rise in energy productivity constitutes a beneficial supply-side shock to the economy, which lowers the price and increases the output of energy-intensive industries relative to other sectors, and output across the whole economy. Depending on economic structure, parameter values for key elasticities, and assumptions about how labour markets function, the net effect can be to *increase* per capita pollution (e.g. tonnes of CO_2 per capita) for every (monetary) unit of GDP ("backfire"). Thus, in looking at the relative effects of improving the productivity of inputs, it is important to model these general equilibrium effects on output and pollution.

This paper therefore uses computable general equilibrium (CGE) analyses to consider the likely impact of technological progress, as represented by energy efficiency improvements, on an economy's position on the EKC curve. The use of CGE models to analyse economy-environment interactions is now widespread in the literature (see Bergman, 2005, for a review), although few papers use CGE models to investigate the EKC. Technological progress has been incorporated into numerous CGE models as an augmenting exogenous coefficient in the production function (for example, Gerlagh and Van der Zwann, 2003). Other papers incorporate technological change through factor productivity increases through innovations in R&D (for example, Popp, 2004; Fisher-Vanden and Ho, 2010). Loschel (2002) surveys how technological change is treated in the environmental-economic models in the literature, observing that the treatment of technological improvements as endogenous in economic models can lead to cost reductions, positive spillovers and pollution leakage, all of which can be argued to place a country favourably on the EKC curve. Pollution leakage could occur, for example, if changes in relative input or output prices brought about by technological improvements result in a loss of output from “dirty” industries, with imports being used to substitute for this lost output. This “leakage” would result in domestic pollution levels falling even though foreign pollution levels are rising, to meet the increased demand for exports. Popp (2004) incorporates an endogenous technological change into the DICE model of climate change to compare the welfare costs of carbon policy against models that treat technological change as exogenous. Fisher-Vanden and Ho (2010) consider the impacts of increased R&D activity on factor input shares and the energy intensity of GDP in China. Das et al (2005) examine the effects associated with environmental and technological policy shifts in the US forest sector by using a multiregional CGE model.

Contributing specifically to the EKC literature, Bruvoll et al (2003) use a CGE model with an endogenous environmental policy for the Norwegian economy to examine the main drivers of the EKC hypothesis for a developed country. They find that there is an inverse relationship between most pollutants and growth. Vickstrom (2004) notes that the even though the rebound effect and the EKC are treated separately, when looking at technological change it can be instructive to look at the two phenomena together. For other CGE contributions that consider the EKC hypothesis (but without specific focus on technological progress) see the review in Bruvoll et al (2003).

3. The AMOSENVI energy-economy-environment CGE model of the Scottish economy

This section provides a broad overview of the structure of the model, highlighting the elements of specification that are most important for the current analysis. A fuller description of the modelling framework is provided in Appendix 1.

3.1 General structure

The model is calibrated on a 1999 Social Accounting Matrix (SAM) for Scotland (see Hanley et al, 2009, for details). It has 3 transactor groups (households, corporations, and government); and 25 commodities and activities, 5 of which are energy commodities/supply: coal; oil; gas; renewable and non-renewable electricity (see Figure 1 and Appendix 2 for details). Scotland is modelled as a region of the UK, with 2 exogenous external transactors, the Rest of the UK (RUK) and the Rest of the World (ROW).

The 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, cost minimisation is imposed 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. In the current application, we assume that real government expenditure is exogenously determined. Consumption is a linear homogeneous function of real disposable income. The external regions (RUK and ROW) are exogenous, but external demand for Scottish exports is sensitive to changes in Scottish prices relative to (exogenous) external prices. See equation (19) in Appendix 1, which takes a CES form. All other determinants of export demand are exogenous. Imports to Scottish production sectors and final consumption are also sensitive to changes in relative prices between (endogenous) domestic and (exogenous) external prices in a standard CES Armington relationship (Armington, 1969). Investment is a little more complex as discussed below in Section 3.3.

3.2 Labour market

Labour market specification is a crucial determinant of results in any CGE analysis. Here, a single local labour market is imposed and characterised by perfect sectoral mobility. In our base case scenario, wages are determined via a bargained real wage function in which the real consumption wage is directly related to workers' bargaining power, and therefore inversely to the unemployment rate (Blanchflower and Oswald, 1994; Minford et al, 1994). We parameterise the bargaining function from the regional econometric work reported by Layard et al (1991):

(1) $$w_{L,t} = \alpha - 0.068u_L + 0.40w_{L,t-1}$$

where: w_L and u_L are the natural logarithms of the local real consumption wage and the unemployment rate respectively, t is the time subscript and α is a calibrated parameter.[1] Empirical

[1] Parameter α is calibrated so as to replicate the base period. 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 one.

support for this "wage curve" specification is now widespread, even in a regional context (Blanchflower and Oswald, 1994).

In the base case scenario, endogenous migration is incorporated in the model (i.e. labour can freely migrate from the rest of the UK) so that population adjusts between time periods (years). Net migration is positively related to the real wage differential and negatively related to the unemployment rate differential between Scotland and RUK and is based on the model of. Harris and Todaro (1970), which has commonly been employed in studies of UK migration (Layard et al, 1991) and US migration (e.g. Greenwood et al, 1991; Treyz et al, 1993). 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 capital stocks (below). The regional economy is initially assumed to have zero net migration and ultimately net migration flows re-establish this population equilibrium. The migration function we adopt is therefore of the form:

(2) $$m = \beta - 0.08\left(u_s - u_r\right) + 0.06\left(w_s - w_r\right)$$

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 RUK real consumption wage and unemployment rates, respectively, and β is a calibrated parameter. Again, we parameterise the migration function from the regional econometric work reported by Layard et al (1991)

However, in order to examine the impact of these labour market configurations on the EKC relationship, in Section 4 we also examine the sensitivity of our results to wage setting and migration behaviour, which are generally taken to be key elements of regional labour market behaviour. Thus, our central case scenario is labelled Flex/Flex (representing flexible real wages, determined through the bargaining function in (1), and flexible population, determined through the migration function in (2). In order to examine the impact of migration alone, we also include a scenario labelled Flex/Fixed, where the real wage is determined through (1) but the Scottish regional population is fixed with migration turned off. In the third scenario, Fixed/Fixed, the real wage is also fixed.

3.3 Capital and investment

The other factor of production that will be important in determining substitution and other effects that drive the economy-wide response, and specifically rebound effects, from increased energy efficiency is capital (see Turner, 2009). Here, within each period, both the total capital stock and its sectoral composition are fixed, and commodity markets clear continuously. Each sector's capital stock is then 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. 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.

This treatment is wholly consistent with sector investment being determined by the relationship between the capital rental rate and the user cost of capital. The capital rental rate, or return on capital, is the rental that would have to be paid in a competitive market for the (sector specific) physical capital while 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 (and vice versa – see Turner, 2009). 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. We assume that interest rates are fixed in international capital markets, so that the user cost of capital varies with the price of capital goods.

3.4 Treatment of energy and other inputs to production

The other key element of model specification, particularly in terms of determining the anticipated substitution effect away from energy in response to an increase in energy efficiency is the specification of the production function.

Figure one here

Figure 1 summarises the production structure of the model. 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 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 directly combining with capital (e.g. Bergman, 1988, 1990), or within the intermediates nest (e.g. Beauséjour et al, 1995). The latter approach may seem appropriate where the energy is a produced (intermediate) rather than a non-produced (primary) input. However, the former approach reflects a long-standing debate in the literature regarding the direct relationship between capital and energy (specifically, whether the two are complements or substitutes in production). In this respect, the decision over where to place energy within a production function is in many ways an aggregation issue. That is, if two inputs are believed to be complements or perfect substitutes, it would be appropriate to nest them together. However, if there is some degree of imperfect substitutability, it is possible to separate them, but with the implication that whatever other inputs either one of these is nested with must share the same degree of substitutability with the other. For example, if energy is nested with materials, then both must substitute equally well with capital, and if capital is nested with labour then both must substitute equally well with all intermediates.

In our current research (see Lecca et al, 2010), we note that, despite the active debate regarding the appropriate way to introduce energy to production functions, what is absent from this literature is any attempt to test the sensitivity of CGE model results to alternative nesting possibilities. We go on to attempt to redress this by conducting both systematic and random parameter variation within alternative KLEM production structures in a Scottish CGE model in response to an economic disturbance (taking the simple example of an exogenous demand shock). Our conclusion is that where there is (a) variation in the elasticity of substitution between different inputs, and (b) changes in relative input prices (as would be the case where efficiency in the use of any one input changes), nesting structure *does* impact the stability of CGE model results. In particular, we find that, in conditions where the supply of capital is constrained, nesting energy alongside capital causes model results with respect to energy use in production to be more sensitive to variation in the values assigned to elasticities of substitution at different nests in the production function (particularly at the energy-capital nest). This is because of the relative importance of the price of capital in determining output prices in all sectors of the economy and the consequent impact on the price of the energy-capital composite. Thus, a conclusion of this study is that a priority of future research must be to attempt to econometrically determine the appropriate nesting and parameterisation of production functions for particular sectors and/or economies under study.

Here, we adopt the approach of positioning energy with other produced inputs in the intermediates composite. However, in recognition of the fact that any particular placing of the energy input in a nested production function restricts the nature of the substitution possibilities between other inputs and in the absence of econometric estimates of the appropriate structure and parameterisation of the nested production function[2], we proceed by assuming a common value for the elasticity of substitution at the K-L, E-M and KL-EM nests. This produces the same results regardless of the nesting of the KLEM inputs. However, as in the approach of Fisher-Vanden and Ho (2010), we carry out sensitivity analysis of the values assigned (see below). In future research, we aim to develop the Lecca et al (2010) model (which has specified at a highly aggregated level, with only a composite energy sector, to focus on more analytical work) in order to facilitate more extensive sensitivity analysis with respect to nesting structure as well as parameterisation.

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. 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.

As noted above, econometric estimates of key parameter values are not currently available for the Scottish CGE model. Previous work simulating efficiency improvements using AMOSENVI (Hanley et al, 2009) suggests that key parameters for the type of simulations reported here are price elasticities of import and export demand and elasticities of substitution in production. In the simulations reported in Sections 4, the Armington trade elasticities are generally set at 2.0 (Gibson, 1990), with the exception of exports of renewable and non-renewable electricity, which are set at 5.0 to reflect the homogeneity of electricity as a commodity in use. Turner (2008, 2009) reports results of sensitivity analyses of the impact of the value of trade parameters on the results of simulating increased energy efficiency.

However, in line with early results reported by Saunders (1992), Turner's (2008, 2009) analysis suggests that a key set of parameters in determining whether increased efficiency in the use of a

[2] At the time of writing, we are currently engaged in the process of econometrically estimating the structure and parameter values for KLEM production functions at the industry level for the case of the UK (following the method developed by Van Der Werf, 2008). Unfortunately, data are not currently available to do the same for Scotland.

factor input reduces or increases the use of that factor is elasticities of substitution between inputs in the nested KLEM production structure in Figure 1. Therefore, in the simulations reported in Sections 4 we set the elasticity of substitution at three key nests in the multi-level production function first at a lower inelastic value of 0.4, then at a mid-point of 0.8, and finally at an elastic one of 1.1 (the 0.4-0.8 range is in line with Kemfert's (1998) findings for the elasticities of substitution between energy/capital and labour/capital for Germany, while the fuller 0.4-1.1 range is in line with Griffin and Gregory's (1976) findings for the UK.[3] These nests are where capital and labour combine to produce value-added, where the energy and non-energy composites combine to give total local intermediates, and where total intermediates combine with value-added to produce sectoral outputs.[4] The approach of testing the sensitivity of model results to a range of values for elasticities of substitution in production is in line with that adopted by Fisher-Vanden and Ho (2010), who, in the absence of econometric estimation to inform production functions for China, initially adopt Cobb Douglas technology (equivalent to assuming an elasticity of 1). They then rerun their simulations using CES technology with "higher" and "lower" (op cit, p.107) values to test the qualitative sensitivity of their results (direction of effects) to this key element of model specification.

Finally, we relate emissions of CO2 to different types of fuel use at different levels of the energy composite (locally-supplied energy inputs) in Figure 1 (see Hanley et al, 2009, for details on data used). Emissions per unit of energy use in final consumption are also modelled. We also include an output-pollution component for the generation of CO2 emissions in addition to the input-pollution links. This reflects the argument of Beauséjour et al (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 (for example, emissions that occur during oil and gas extraction activities).

4. Simulating the impacts of increased energy efficiency on the CO2 intensity of GDP

In this section we consider the impact of increased efficiency in the use of energy in production activities on the EKC curve for Scotland, defined in terms of pollution generated within the geo-political borders of Scotland. That is, we examine whether technological progress results in increased prosperity (represented by GDP) accompanied by a relative reduction in both absolute and per capita

[3] As noted in Footnote 2, we are currently in the process of updating on Griffin and Gregory's (1976) estimates for the UK KLEM production function.
[4] Although, as noted above, our imposition of common values at each of these nests effectively translates to a single level CES function for these substitutions.

pollution levels (here represented by emissions of the main greenhouse gas, CO_2) generated in the Scottish economy. The technological progress takes the form of increased efficiency in the use of energy as an input to production. If GDP rises faster than CO_2 emissions per capita, this implies that technological change moves the economy *along* the EKC towards a possible turning point, since we have a reduction in the per capita CO_2 intensity of GDP. However, to pass the turning point and move onto the downward section of the EKC requires that per capita pollution levels actually fall as GDP rises, (rather than GDP rising faster than CO_2 per capita). Both effects can be tested for.

In our results we focus on both the absolute and relative (per capita) EKC relationship. The former (tonnes of CO_2 per £1m GDP) is the key result in terms of the general policy aim to reduce absolute CO_2 emissions while still achieving economic growth. When we move to an EKC per capita measure, it is important to note that we define this in terms of physical CO_2 per capita relative to the absolute measure of GDP. This approach is taken because of the importance of migration and population change in determining how the economy adjusts to a new equilibrium (and the level and nature of activity therein). We take absolute GDP as the most relevant measure of economic growth in the present context because it is possible for GDP per capita to rise while GDP itself falls (i.e. the economy contracts) if population were to fall faster than GDP. This may happen as a result of out-migration if economic conditions were to decline. In the simulations reported here, GDP always rises because the energy efficiency improvement introduced is a positive supply shock (a productivity improvement), and always faster than population growth, with the implication that GDP per capita (as a measure of individual prosperity) will always rise in the simulations reported here, but by less than absolute GDP growth. We include sensitivity analysis of how our results would be affected by attaching the per capita element of the EKC relationship to GDP rather than to CO_2.

4.1 Simulation strategy and theoretical considerations

We introduce a very simple and illustrative 5% exogenous (and costless) increase in energy efficiency in all production sectors.[5] Simulation of a simple shock such as this is an important first step as it allows us to consider the main basic drivers of general equilibrium responses to improvements in energy productivity. We introduce the energy efficiency shock by increasing the

[5] For a treatment where energy improvements are costly, see Allan et al (2007).

productivity of the energy composite in the production structure of all industries.[6] This is energy-augmenting technical change. We distinguish energy measured in natural or physical units, E, from energy measured in efficiency units, ε (i.e. the effective energy service delivered). If we have energy augmenting technical progress at a rate ρ, the relationship between the proportionate change in E and ε is given as:

(3) $$\dot{\varepsilon} = \rho + \dot{E}$$

This implies that an *x*% increase in energy efficiency has an impact on output (associated with a given amount of physical energy use) that is identical to an *x*% increase in energy inputs without the efficiency gain. The direct impact of this exogenous shock is that the increase in energy efficiency has a corresponding impact on the price of energy, when energy is measured in efficiency units. Specifically:

(4) $$\dot{p}_{\varepsilon} = \dot{p}_{E} - \rho$$

where p represents price and the subscript identifies energy in either physical (E) or efficiency (ε) units. If we assume (for now) constant energy prices in physical units, an *x*% improvement in energy efficiency generates an *x*% reduction in the price of energy in terms of efficiency units, or an *x*% reduction in the implicit or effective price of energy.

With physical energy prices constant, a decrease in the price of energy in efficiency units will generate an increase in the demand for energy in efficiency units. This is the source of the rebound effect and the key determinant of the change in energy use and CO2 emissions levels in response to the increase in technological progress. In a general equilibrium context:

(5) $$\dot{\varepsilon} = -\eta \dot{p}_{\varepsilon}$$

where η is the general equilibrium price elasticity of demand for energy which has been given a positive sign. For an energy efficiency gain that applies across all uses of energy within the

[6] We do not change the efficiency with which energy is used in the household or government consumption, investment, or export final demand sectors. Moreover, note that under the current production structure in Figure 1, we are only able to apply the efficiency shock to use of local energy, and not imports.

economy, the change in energy demand in natural units can be found by substituting equations (4) and (5) into equation (3), giving:

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

This tells us that the general equilibrium price demand for energy in efficiency units is the driver of changes in energy consumption and energy-related emissions.

However, while the simple conceptual approach in equations (3)-(6) would be appropriate 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 two problems that will introduce greater complexity in the analysis of real economies. The first is that energy is also produced domestically with energy as one of its inputs, with the implication that the price of energy in physical units will be endogenous, giving further impetus a change in the change in energy demand in (5). While primary energy prices are likely to be set exogenously (e.g. setting of oil prices by OPEC) and/or determined on international markets, where there is local refining/production of energy inputs such as refined petroleum and electricity, and/or variations in capacity and transport costs at the local level, it is possible for energy supply prices to be co-determined by local (ie country-specific) factors.

The second problem is that of identifying of the general equilibrium elasticity of demand for energy, η, in (5) and (6), which is shown by Turner (2008, 2009) above to be the crucial determinant of the size of changes in energy consumption and, consequently rebound effects in response to a given change in energy augmenting technological progress. 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 the theoretical analysis of Allan et al (2009) demonstrates. As well as elasticities of substitution in production, which tend to receive most attention in the literature (see Broadstock et al, 2007, for a review) crucial factors 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). Allan et al (2009) also show that which sectors of the economy benefit from the exogenous technical progress is also important in terms of the resultant rebound effects. Thus, the extent of rebound effects is, in practice, always an empirical issue.

Here we begin with our central case scenario where the 5% increase in (exogenous) energy-augmenting technological progress is introduced to all 25 production sectors in the Scottish economy. Capital stock adjusts over time through investment (as detailed in Section 3.3) and labour supply adjusts (along with total population) through migration in response to changes in the Scottish unemployment and wage rates relative to those in the rest of the UK (as detailed for the Flex/Flex labour market case in Section 3.2).

Our first test of sensitivity is to then examine the impact of varying the elasticity of substitution of energy for other inputs, by varying the values assigned to the three key KLEM production elasticities (capital-labour, energy-non energy intermediates and total intermediates-value-added), initially set at a price inelastic (<1) value of 0.4, then raised to a mid-point of 0.8 and then to an elastic (>1) value of 1.1. The second test of sensitivity is to vary the labour market specification by holding labour supply and population fixed but with the real wage variable in the Fixed/Flex case, and then with both wages and population fixed. The third test is to limit the efficiency improvement to the 20 non-energy-supply sectors (sectors 1-20 in Appendix 2), thus excluding the most energy-intensive sectors and the anticipated pressure for 'backfire' effects (net increases) in energy consumption. Finally, we examine the impact of changing the structure of the economy on the relationship between energy efficiency and the EKC, by comparing the Scottish results with a comparable set from a comparable CGE model of the UK economy.

4.2 Energy efficiency simulation results

Central case scenario

Table 1 reports the impacts on key aggregate variables of the 5% increase in energy efficiency targeted at all 25 production sectors for the flexible wages/flexible population case under alternative assumptions regarding the substitutability of energy for other inputs. We begin with the most inelastic case, 0.4, in the first two columns. The figures reported are percentage changes from the base year values. Because the economy is taken to be in full (long-run) equilibrium prior to the energy efficiency improvement, the results are best interpreted as being the proportionate changes over and above what would have happened, *ceteris paribus*, without the efficiency shock. In the short-run (the first period after the shock), both labour (population) and capital stocks are assumed to be fixed at the level of individual sectors. In the long run in both cases capital stocks have full adjusted fully to their desired sectoral values, and population has also fully adjusted through migration from the rest of the UK (restoring the real take home wage to its initial value). With wage determination characterised by a bargained wage curve, a beneficial supply-side policy, such as an improvement in energy efficiency, improves competitiveness, increases employment, reduces the unemployment rate and increases real wages. This has a positive impact on economic activity that is generally greater in the long run than in the short run. For the 0.4 case, there is a long run increase of 0.87% in GDP, 0.8% in employment and 0.96% in exports. The expansion is generally lower in the short run, where GDP increases by 0.07%.

Table 1 around here

In terms of energy use, CO2 generation and the CO2 intensity of GDP, there is a decrease in total (economy-wide) electricity consumption of 0.8% in the short run. However, by the long run, this has backfired into a 1.56% increase in energy consumption. For non-electricity energy consumption these figures are -0.69% and 1.1% respectively. The resulting long-run rise in CO2 emissions (1.37%) is larger than the increase in GDP (0.87%) so that the CO2 intensity of GDP increases (by 0.49%). In the short run CO2/GDP falls by 0.66% (due to the short run drop in CO2 of 0.59%). However, over the long-run, in-migration in response to the growth in economic activity (which pushes Scottish real wages up and unemployment down while factor supply is constrained in early periods) leads to a population increase of 0.8%. While CO2 per capita rises after an initial drop (following the short run fall in energy use and CO2 generation), Figure 1 shows that this is by less than the growth in GDP. Thus the CO2 per capita/GDP (our per capita EKC relationship) falls by 0.3% in the long-run. This is a smaller decrease than in the short run (0.66%) when CO2 per capita falls in line with absolute CO2 (there is no population change in the short-run). However, it still suggests that a long run shift of the Scottish economy along the EKC curve so that while absolute CO2 levels are rising, the per capita CO2 intensity of GDP is falling.
Figure 2 here

This result reflects the importance of examining impacts over different time periods. In the short run for this first case, where the absolute level of CO2 emissions falls, the Scottish economy has actually shifted past the turning point of the EKC where pollution levels decrease as the economy grows. See Figure 2 for the adjustment of the key variables determining the EKC relationship over time. However, this is only a temporary outcome. Over time, as supply constraints are relaxed and the economy grows in response to the positive competitiveness and income effects of increased productivity, energy use grows along with the use of all factor inputs and pollution levels rise. Figure 2 shows that after falling in the first year after the shock, within 10 years both CO2 levels and CO2/GDP have risen about their base year levels. Nonetheless, in this first case, where substitutability in favour of energy as its effective (and actual, domestic) price falls with increased efficiency, is set at a relatively inelastic value (0.4), the substitution effect in favour of energy is limited sufficiently that the desired per capita EKC result occurs (in qualitative terms at least) as a result of the rise in Scottish population. However this result is sensitive to the definition of the per capita EKC relationship, as shown below.

The impact of varying the elasticity of substitution between energy and other inputs

Considering Table 1, we see that while the short run growth in the economy is greater with a substitution parameter of 0.8 rather than 0.4, the effects are relatively smaller in the long run. This is partly because the greater substitutability in favour of energy limits the growth in capital and labour (under 0.8 investment grows by 0.96% compared to 1.01% under 0.4, and employment by 0.77% compared to 0.8%). However, the short-run greater pressure for growth in the 0.8 case puts more upward pressure on Scottish real wages in the short run (see Figure 3), which limits the positive competitiveness effects of the efficiency improvement (i.e. Scottish production costs in terms of labour, which is the dominant input, are driven up). Thus, despite the larger short-run growth in Scottish real wages (and fall in unemployment), the long run stimulus to population is lower (see Figure 3) along with the growth in other macroeconomic indicators.
Insert Figure 3

On the other hand, with the elasticity of substitution raised to 0.8, the third and fourth columns of Table 1 show greater increases in energy consumption relative to the 0.4 case, with backfire effects (net increases in energy use) from the short run. This leads to an increase in absolute levels of CO2 generation that again outstrips GDP so that the overall CO2 intensity of GDP rises by 0.94% in the short run and 1.78% in the long run (and this is compounded relative to the 0.4 case, where long-run CO2/GDP rises by 0.49% given that the higher CO2 growth is set against lower GDP growth). As in the 0.4 case, population also increases (by 0.77% in the long run) but this is not sufficient to prevent an increase in the per capita EKC measure for Scottish CO2 of 0.94% in the short run and 1% in the long run (again, see Figure 3 for the time path of adjustment in this measure relative to the 0.4 case).

The last two columns of Table 1 show that the situation described above for the 0.8 case is exacerbated when the substitution effect driving rebound is increased to a price elastic value of 1.1. Again, short run economic growth is greater but long run growth is more limited, but this is accompanied by bigger backfire effects. That the 0.8 and 1.1 results are qualitatively similar (i.e. the direction of effects is the same on all variables) demonstrates that the substitution effect in favour of energy in production is not the only key factor in determining the general equilibrium price elasticity of demand for energy in equation (6) for the central case scenario (all 25 sectors shocked, flexible wages and population). If the substitution effect were the only determinant, Cobb Douglas technology (i.e. elasticity of 1) would be required to induce a rebound effect of 100% and entirely offset the energy savings from the efficiency increase. This suggests that competitiveness and/or income effects are also very important in the Scottish case. We turn our attention to the impact of competitiveness effects in particular below, as previous research reported by Hanley et al (2009) suggests that these are dominated by the impacts of the export demand response for the outputs of the (relatively energy intensive) Scottish energy supply sectors. However, we first turn our attention to the impacts of varying the labour market specification, given that the initial results in Table 1 suggest that migration in particular is important in determining the desirable long run per capita EKC result in the 0.4 case above.

The impact of varying the labour market specification

Table 2 here

Table 2 shows the sensitivity of the CO2, CO2/GDP and per capita EKC results for under the three alternative labour market specifications identified in Section 3.2 (for each of the three elasticity of substitution cases: 0.4, 0.8, 1.1). The top set of results are where both the real wage and population are fixed (Fixed/Fixed), the second where the real wage varies according to equation (1) but population remains fixed (Flex/Fixed) and the third is the central case scenario where both real wages and population are flexible (Flex/Flex). One thing to note (not reported in the table), is that the long-run economic growth is most limited where real wages are allowed to vary but population is not. This is because having variable real wages without the pressure of in-migration will have lasting negative competitiveness effects. Where both wages and population are fixed, growth will still be limited relative to the central case where they are flexible but to a much lesser extent than when only population is fixed and the permanent rise in real wages damages competitiveness.

However, in terms of the EKC impacts of different labour market settings, Table 2 shows that there is no great difference among the labour market specifications in terms of the absolute change in CO2 emissions. Across each scenario, this is most limited in the flexible real wage/fixed population scenario, where growth is almost most limited. However, the change in the CO2/GDP ratio is also similar in each case. The key difference in the results in Table 2 is that the positive per capita EKC outcome (i.e. the long drop of 0.3%) of the 0.4 central case scenario is lost when migration is not possible: in the 0.4 long-run result for the Flex/Fixed scenario we now have a long run rise in per capita emissions as a ration of GDP of 0.48%.

Therefore, the conclusion we can draw here is that, where all production sectors in the Scottish economy are targeted with an energy efficiency improvement, as well as requiring relatively inelastic substitution in favour of labour (here 0.4), migration of labour is also crucial. The results in Table 2 show that this is what allows the Scottish economy to move along the EKC curve to a point where per capita CO2 intensity of GDP is falling (but only in the most inelastic elasticity of substitution case). In all other cases, the long run outcome for Scotland is on the upward portion of the EKC where CO2 and the per capital CO2 intensity of economic activity is rising as the economy grows.

The impact of redefining economic growth in terms of GDP per capita in the per capita EKC relationship

The analysis above shows that migration is crucial in delivering the result of moving the Scottish economy past the turning point of the per capita EKC curve over the long-run (coupled with the limited elasticity of 0.4). However, as we saw in Figure 2, CO2 per capita actually rises, even with in-migration of labour (and, thus, population growth); the key point is that GDP rises faster. However, in Figure 4, we show the results of redefining the EKC per capita relationship, stating GDP rather than CO2 in per capita terms.

Insert Figure 4

Figure 4 shows that in our central case scenario, while in the early periods absolute and CO2 per capita both fall, over time both CO2 and GDP both rise faster than population with implication that both pollution and economic activity per capita rise as the economy adjusts towards long-run equilibrium. However, while CO2 per capita still grows slower than GDP growth, producing the positive EKC per capita result (a long-run shift by the turning point), GDP per capita growth is much more limited (due to population growth tracking GDP growth fairly closely) and significantly lower than CO2 growth. Thus, if we take the EKC per capita relationship to be defined in terms of absolute CO2 per unit of per capita GDP growth Figure 4 shows that it moves in completely the opposite direction to the central case measure. Moreover, it outstrips GDP growth, which the absolute EKC relationship (CO2/GDP) does not. Thus, even with migration, if we change the definition of the EKC per capita relationship the positive picture in the long-run is lost altogether, with increased energy efficiency violating the EKC hypothesis that technological progress will allow the economy to move past the turning point of a U-shaped curve in either relative or absolute terms.

The impact of limiting the shock to non-energy supply sectors

The impacts of energy efficiency changes on pollution would seem likely to be sensitive to which sectors benefit from the efficiency increase. In the model runs reported so far, all sectors are assumed to experience a 5% increase in technical energy efficiency. Scottish electricity production and distribution sectors are heavily traded and relatively energy intensive. Therefore, when their efficiency in the use of energy is boosted, there are strong positive competitiveness effects that drive economic expansion and increased energy use. An interesting question is thus what would happen if these sectors, for some reason, are excluded from the efficiency improvement. Table 3 is comparable with Table 1, the only difference being that energy efficiency improvement is limited to sectors 1-20, i.e. the energy supply sectors are excluded from the productivity shock (we return to the central case scenario in terms of the labour market, with flexible wages and population).

Table 3 here

The first thing to note in comparing Tables 1 and 3 is that the positive economic impacts of the efficiency improvement are significantly curtailed when the five (relatively energy-intensive) energy supply sectors are not directly targeted with the shock. On the other hand, while rebound in energy use is present in all cases, this only becomes backfire (over any time period) where the key elasticities of substitution are set over 1 (elastic). Thus, the substitution effect is more important in determining the general equilibrium price elasticity of demand for energy in the simulations reported in Table 3. In terms of the environmental effects, from the outset in the 0.4 and 0.8 cases the Scottish economy moves past the turning point of the EKC curve where both the absolute level of CO2 emissions and the CO2 intensity (both per capita and absolute) of activity is falling. That is the EKC hypothesis holds in both absolute and relative terms. This is a more clear-cut and positive outcome than the 0.4 outcome in the central case scenario given the drop in absolute levels of CO2. Moreover, while it is not reported in Table 3, the EKC per capita variable falls under the alternative definition (with GDP per capita in the denominator), by -0.95% in the 0.4 case, which is a smaller drop than in under our central measure, -1.24% in Table 3, but further reinforces the consistency of results with the EKC hypothesis.

However, note from the fourth column of Table 3 that by the long-run in the 0.8 case, excluding the energy supply sectors from the efficiency improvement takes the Scottish economy only very marginally past the turning point of the EKC with only a 0.02% drop in CO2 levels relative to the base year. The CO2 intensity of GDP falls by 0.28%. Again the direction of the per capita EKC relationship is not sensitive to its definition: in Table 3 the per capita CO2 intensity of GDP falls by 0.53% and, while again not reported, there is 0.27% drop in CO2/GDP per capita.

Impacts of a different economic structure: results from a UK equivalent model.

Table 4 here

The effects of an improvement in energy efficiency on pollution and GDP may also depend on the broader structure of an economy, for example in terms of the relative importance of the energy sector, the energy content of exports, and the relative importance of high energy intensity industries such as cement manufacture and steel refining. To investigate this empirically, we have constructed a comparable CGE model for the UK (UKENVI – see Appendix 3 for sectoral breakdown, which includes the same 5 energy supply sectors, but slightly different classification of the other 20) to allow us to contrast results with those from our Scottish model.[7] UKENVI is based on the same generic CGE model as AMOSENVI, but calibrated on a UK SAM for 2000: Figure 1 and Appendix 1 highlight some key differences, but for fuller details on the UKENVI model see Allan et al. (2007) and Turner (2009). Here, the key distinction we take as relative to the Scottish central case scenario is to hold the national population fixed, partly because labour cannot in practice migrate internationally as easily as it can inter-regionally (as specified in equation 2). This means that the absolute and relative EKC results will be identical.

[7] The differences in sectoral breakdown in the UKENVI model relative to its Scottish counterpart, AMOSENVI, reflect different policy concerns at the time of model construction (see Allan et al, 2006).

However, the main reason that we select the flexible wage/fixed population case to report for the UK is that, as shown in Tables 4 and 5 below, migration is not required to bring about a long-run reduction in the per capital EKC measure even where all 25 production are directly targeted with the efficiency improvement. This outcome is summarised in the last column of Table 5 below. Moreover, this outcome is achieved even with a value of 0.8 on the elasticity of substitution between energy and other inputs. The summary in Table 5 shows that the drop in per capita EKC is reversed in the Scottish case when we move from 0.4 to 0.8 within the Flex/Flex case (with migration) and that the increase becomes larger we move to the Flex/Fixed (no migration). Economic structure thus appears to be an important determinant of the effects of energy efficiency improvements on pollution intensity per capita, when the elasticity of substitution of energy for other inputs is less than one.

Table 5 here

The key difference between the UK and Scottish economies underlying these results is that the UK energy supply sectors are much less open to trade than their Scottish counterparts. This means that, in the case of the UK, positive competitiveness effects as a result of falling energy sector output prices are a less important determinant of the general equilibrium price elasticity of demand for energy that drives the rebound effect. Thus, in the UK case in contrast to that of Scotland, it is possible for the economy to move onto that part of the EKC curve where the CO2 intensity of the economy is falling even when energy-intensive energy supply sectors directly benefit from an energy efficiency improvement. However, the results in Table 4 show that relatively inelastic substitution possibilities are required in production (here, 0.4) to limit the substitution effects driving rebound sufficiently that the economy can move past the turning point of the EKC so that *absolute* levels of CO2 fall as the economy grows.

5. Conclusions and directions for future research

In this paper we examine the conditions under which increased efficiency in the use of energy as an input to production impacts on absolute pollution levels, pollution relative to GDP, and pollution per capita. Reductions in pollution intensity move the economy along the EKC. Reductions in absolute emissions move the economy down the EKC (past a turning point). Improvements in energy efficiency produce a range of general equilibrium effects: a pure efficiency change, which reduces emissions and energy use, and substitution, competiveness and structural change effects, which tend to increase energy use and a “rebound” in emissions. If countervailing effects outweigh the pure efficiency effect then the rebound effect becomes a backfire effect.

Knowing what factors contribute to such movements, and how important these contributions are, is of interest both from a policy perspective, and from the perspective of academic enquiry. We quantify the relative importance of a number of such factors. These include the elasticity of substitution of energy for other inputs, the time period under consideration, whether labour supply can increase via migration in response to higher real wages, and which sectors of the economy are affected by the energy efficiency improvement.

For both our Scottish and UK case studies we find that, when the general equilibrium price elasticity of demand for energy is below one (i.e. relatively inelastic) the economy *may* move onto the downward part of the EKC, with CO2 emissions actually falling as GDP rises. If the general equilibrium price elasticity of demand for energy rises above one, backfire effects occur and the economy is on the upward part of the EKC, with energy use and CO2 emissions rising faster than GDP. However, we find that the general equilibrium price elasticity of demand for energy depends on which production sectors are directly affected by the efficiency improvement, and on the structure of the economy (in particular, the greater trade in energy in the Scottish case tends to increase the strength of rebound effects, with competitiveness rather than substitution effects playing the dominant role in determining the magnitude of rebound). We also find that the time period under consideration is also crucial as the direction of effects can differ over time, particularly where rebound grows into backfire. In the Scottish case, another important factor in the time path of adjustment for the per capita EKC measure is whether the labour supply can adjust through migration, but also the precise definition of the per capita measure.

One element of the work reported here that requires further research is to specify and parameterise the nested production function that applies in each sector of the economy. The sensitivity analysis reported here demonstrates that the values attached to key elasticity of substitution parameters are crucial in determining both the quantitative and qualitative nature of results. However, we have not yet been able to test the sensitivity of our results to alternative nesting structures. If we draw inference from the conclusions of Lecca et al (2010), it is likely that, where elasticities vary between different nests, and where there are constraints on capital and/or labour (causing variation in the price of these primary inputs) the adjustment path of our results may be more volatile if energy were nested within the value-added rather than the intermediates composite. Recognising the importance of this issue, we are currently engaged in work, initially following the approach of Van der Werf (2008), to estimate sectoral KLEM production functions (both specification and parameterisation), albeit only at the UK national level (data are not currently available to facilitate region-specific estimates for Scotland).

It would also be interesting to simulate an energy efficiency improvement in the context of an accompanying carbon tax: governments tend to announce packages of climate change messages, and combining energy efficiency improvements with a carbon tax would offset the rebound effect, but also lessen the "pain" of carbon taxes to the economy in terms of lost GDP growth, since the economy experience a beneficial supply side shock. A third extension would be to endogenise the technological improvement in energy use: in this paper, technology improves exogenously and costlessly. It would also be useful to examine the relationship between technological progress and the EKC in an interregional or international context, with specific focus on emissions under consumption rather than a production accounting measure of emissions. This would allow us to address issues relating to the pollution leakage hypothesis in the context of EKC, identified by Arrow et al (1995) as a possible explanation as to why richer countries can become richer while reducing pollution levels.

Finally, another direction for future research will be to consider technological progress in terms of factors of production other than energy. For example, if efficiency in the use of labour and/or capital were to increase, competitiveness and income effects would be expected to increase activity levels throughout the economy, and thus the use of all inputs to production (including energy). However, the substitution effect would be in favour of the factor targeted, and away from energy use. Thus, the impact in terms of CO_2 generation, and the CO_2 intensity of economic growth would be, in a sense, more stable.

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Appendix 1. A condensed version of the AMOSENVI framework

(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) Short-run capital supply	$K_i^s = \bar{K}_i^s$
(8) Long-run capital rental	$w_{k,i} = uck(kpi)$
(9) Capital price index	$kpi = \sum_i \gamma_i \; pq_i + \sum_i \gamma_i^{RUK} \; \bar{pq}_i^{RUK} + \sum_i \gamma_i^{ROW} \; \bar{pq}_i^{ROW}$
(10) Labour demand	$N_i^d = N_i^d(V_i, w_n, w_{k,i})$
(11) Capital demand	$K_i^d = K_i^d(V_i, w_n, w_{k,i})$
(12) Labour market clearing	$N^s = \sum_i N_i^d = N$
(13) Capital market clearing	$K_i^s = K_i^d$
(14) Household income	$Y = \Psi_n N w_n (1 - t_n) + \Psi_k \sum_i w_{k,i} (1 - t_k) + \bar{T}$
(15) Commodity demand	$Q_i = C_i + I_i + G_i + X_i + R_i$

(16) Consumption Demand	$C_i = C_i\left(pq_i, \overline{p}q_i^{RUK}, \overline{p}q_i^{ROW}, Y, cpi\right)$
(17) Investment Demand	$I_i = I_i\left(pq_i, \overline{p}q_i^{RUK}, \overline{p}q_i^{ROW}, \sum_i b_{i,j} I_j^d\right)$ $I_j^d = h_j\left(K_j^d - K_j\right)$
(18) Government Demand	$G_i = \overline{G}_i$
(19) Export Demand	$X_i = X_i\left(p_i, \overline{p}_i^{RUK}, \overline{p}_i^{ROW}, \overline{D}^{RUK}, \overline{D}^{ROW}\right)$
(20) Intermediate Demand	$R_{i,j}^d = R_i^d\left(pq_i, pm_j, M_j\right)$ $R_i^d = \sum_j R_{i,j}^d$
(21) Intermediate Composite Demand	$M_i = M_i\left(pv_i, pm_i, Q_i\right)$
(22) Value Added Demand	$V_i = V_i\left(pv_i, pm_i, Q_i\right)$

NOTATION

Activity-Commodities

i, j are, respectively, the activity and commodity subscripts (There are twenty-five of each in both AMOSENVI and UKENVI, see Appendices 2 and 3.)

Transactors

RUK = Rest of the UK (AMOSENVI only), ROW = Rest of World (AMOSENVI and UKENVI); all RUK variables drop out in the case of UKENVI.

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

uck User cost of capital

Variables and parameters

C	consumption
D	exogenous export demand
G	government demand for local goods
I	investment demand for local goods
$\mathbf{I^d}$	investment demand by activity
$\mathbf{K^d, K^S, K}$	capital demand, capital supply and capital employment
L	labour force
M	intermediate composite output
$\mathbf{N^d, N^S, N}$	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
$\mathbf{b_{ij}}$	elements of capital matrix
cpi, kpi	consumer and capital price indices
d	physical depreciation
h	capital stock adjustment parameter
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

Appendix 2. Sectoral breakdown of the 1999 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. Sectoral breakdown of the 2000 UKENVI model

		IOC
1	Agriculture, forestry and fishing	1, 2, 3
2	Other mining and quarrying, including oil and gas extraction	5, 6, 7
3	Mfr - Food and drink	8 to 20
4	Mfr – Textiles	21 to 30
5	Mfr - Pulp, paper and articles of paper and board	32 to 33
6	Mfr - Glass and glass products, ceramic goods and clay products	49 to 51
7	Mfr - Cement, lime plaster, plaster, concrete, other non-metallic products	52 to 53
8	Mfr - Iron, steel first processing, and casting	54 to 56
9	Mfr - Other metal products	57 to 61
10	Mfr - Other machinery	62 to 68
11	Mfr - Electrical and electronics	69 to 76
12	Mfr - Other manufacturing	31, 34, 36-48, 77-84
13	Water	87
14	Construction	88
15	Distribution and transport	89 to 97
16	Communications, finance and business	98 to 107, 109 to 114
17	Research and development	108
18	Public admin and education	115+116
19	Health and social work	117+118
20	Other services	119-123
	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)	

Tables

Table 1. Impacts of a 5% increase in energy efficiency in all 25 Scottish production sectors

Flexible real wage/flexible population

% change from base year values

	Base Year Values	Key KLEM elasticities of substitution					
		0.4		0.8		1.1	
		SR	LR	SR	LR	SR	LR
GDP (income measure) (£m)	62,624	0.07	0.87	0.09	0.83	0.10	0.81
Consumption (£m)	44,113	0.20	0.79	0.23	0.76	0.24	0.74
Investment (£m)	10,620	0.37	1.01	0.61	0.96	0.76	0.92
Exports (£m)	47,296	0.23	0.96	0.32	0.97	0.37	0.98
Imports (£m)	50,915	0.06	0.28	0.16	0.29	0.22	0.30
Real T-H consumption wage (£000s)	14	0.11	0.00	0.14	0.00	0.15	0.00
Total employment (000s):	2,006	0.11	0.80	0.14	0.77	0.15	0.75
Unemployment rate (%)	8	-0.94	0.00	-1.19	0.00	-1.27	0.00
Total population (000s)	5,119	0.00	0.80	0.00	0.77	0.00	0.75
Total electricity consumption (tonnes oil equiv)	32,038	-0.80	1.56	1.27	3.22	2.79	4.50
Total non-electricity energy consumption (tonnes oil equiv)	17,998,420	-0.69	1.10	0.83	2.30	1.95	3.21
Total CO2 generation (tonnes)	48,509,902	-0.59	1.37	1.03	2.63	2.22	3.60
CO2 Intensity of GDP (CO2/GDP) (tonnes per £1m)	775	-0.66	0.49	0.94	1.78	2.12	2.77
EKC per capita (tonnes indexed to UK pop=1)	13	-0.66	-0.30	0.94	1.00	2.12	2.01

Table 2. Environmental impacts of a 5% increase in energy efficiency in all 25 Scottish production sectors

% change from base year values

Labour market structure	Key KLEM elasticities	CO2 SR	CO2 LR	CO2/GDP SR	CO2/GDP LR	EKC per Capita SR	EKC per Capita LR
Fixed real wage and fixed population	0.4	-0.57 Fall	1.28 Rise	-0.69 Fall	0.46 Rise	-0.69 Fall	0.46 Rise
	0.8	1.10 Rise	2.55 Rise	0.90 Rise	1.75 Rise	0.90 Rise	1.75 Rise
	1.1	2.31 Rise	3.52 Rise	2.06 Rise	2.74 Rise	2.06 Rise	2.74 Rise
Flexible real wage and fixed population	0.4	-0.59 Fall	0.87 Rise	-0.66 Fall	0.48 Rise	-0.66 Fall	0.48 Rise
	0.8	1.03 Rise	2.19 Rise	0.94 Rise	1.81 Rise	0.94 Rise	1.81 Rise
	1.1	2.22 Rise	3.20 Rise	2.12 Rise	2.82 Rise	2.12 Rise	2.82 Rise
Flexible real wage and flexible population	0.4	-0.59 Fall	1.37 Rise	-0.66 Fall	0.49 Rise	-0.66 Fall	-0.30 Fall
	0.8	1.03 Rise	2.63 Rise	0.94 Rise	1.78 Rise	0.94 Rise	1.00 Rise
	1.1	2.22 Rise	3.60 Rise	2.12 Rise	2.77 Rise	2.12 Rise	2.01 Rise

Table 3. Impacts of a 5% increase in energy efficiency limited to the 20 non-energy supply Scottish production sectors

Flexible real wage/flexible population

% change from base year values

	Base Year Values	Key KLEM elasticities of substitution					
		0.4		0.8		1.1	
		SR	LR	SR	LR	SR	LR
GDP (income measure) (£m)	62,624	0.04	0.29	0.04	0.26	0.03	0.24
Consumption (£m)	44,113	0.11	0.27	0.10	0.25	0.09	0.22
Investment (£m)	10,620	0.16	0.31	0.24	0.29	0.28	0.28
Exports (£m)	47,296	0.08	0.27	0.09	0.28	0.11	0.28
Imports (£m)	50,915	-0.03	0.00	-0.01	0.00	0.00	0.00
Real T-H consumption wage (£000s)	14	0.06	0.00	0.06	0.00	0.05	0.00
Total employment (000s):	2,006	0.07	0.29	0.06	0.25	0.05	0.22
Unemployment rate (%)	8	-0.55	0.00	-0.50	0.00	-0.42	0.00
Total population (000s)	5,119	0.00	0.29	0.00	0.25	0.00	0.22
Total electricity consumption (tonnes oil equiv)	32,038	-1.04	-0.97	-0.23	-0.02	0.42	0.70
Total non-electricity energy consumption (tonnes oil equiv)	17,998,420	-0.72	-0.66	-0.18	-0.02	0.25	0.47
Total CO2 generation (tonnes)	48,509,902	-0.69	-0.66	-0.18	-0.02	0.25	0.47
CO2 Intensity of GDP (CO2/GDP) (tonnes per £1m)	775	-0.73	-0.95	-0.22	-0.28	0.22	0.23
EKC per capita (tonnes indexed to UK pop=1)	13	-0.73	-1.24	-0.22	-0.53	0.22	0.01

Table 4. Impacts of a 5% increase in energy efficiency in all 25 UK production sectors

Flexible real wage/fixed population

% change from base year values

	Base Year Values	Key KLEM elasticities of substitution					
		0.4		0.8		1.1	
		SR	LR	SR	LR	SR	LR
GDP (income measure) (£m)	822,400	0.11	0.17	0.12	0.17	0.12	0.17
Consumption (£m)	626,537	0.37	0.34	0.36	0.34	0.36	0.34
Investment (£m)	153,336	0.06	0.14	0.03	0.16	0.01	0.16
Exports (£m)	256,102	0.01	0.24	0.11	0.30	0.16	0.34
Imports (£m)	273,741	-0.22	-0.21	-0.23	-0.19	-0.24	-0.19
Real T-H consumption wage (£000s)	14	0.30	0.30	0.32	0.28	0.32	0.27
Total employment (000s):	26,602	0.21	0.21	0.22	0.19	0.23	0.19
Unemployment rate (%)	6	-2.59	-2.58	-2.79	-2.44	-2.82	-2.35
Total population (000s)	58,886	0.00	0.00	0.00	0.00	0.00	0.00
Total electricity consumption (tonnes oil equiv)	391,234	-1.97	-2.62	-0.14	-0.45	1.38	1.23
Total non-electricity energy consumption (tonnes oil equiv)	219,856,086	-1.06	-1.65	0.34	-0.02	1.50	1.23
Total CO2 generation (tonnes)	491,581,916	-1.28	-2.09	0.41	-0.08	1.83	1.46
CO2 Intensity of GDP (CO2/GDP) (tonnes per £1m)	598	-1.39	-2.25	0.29	-0.25	1.70	1.29
EKC per capita (tonnes indexed to UK pop=1)	10	-1.39	-2.25	0.29	-0.25	1.70	1.29

Table 5 Summary of per capita EKC impacts of increased energy efficiency in the UK and Scotland

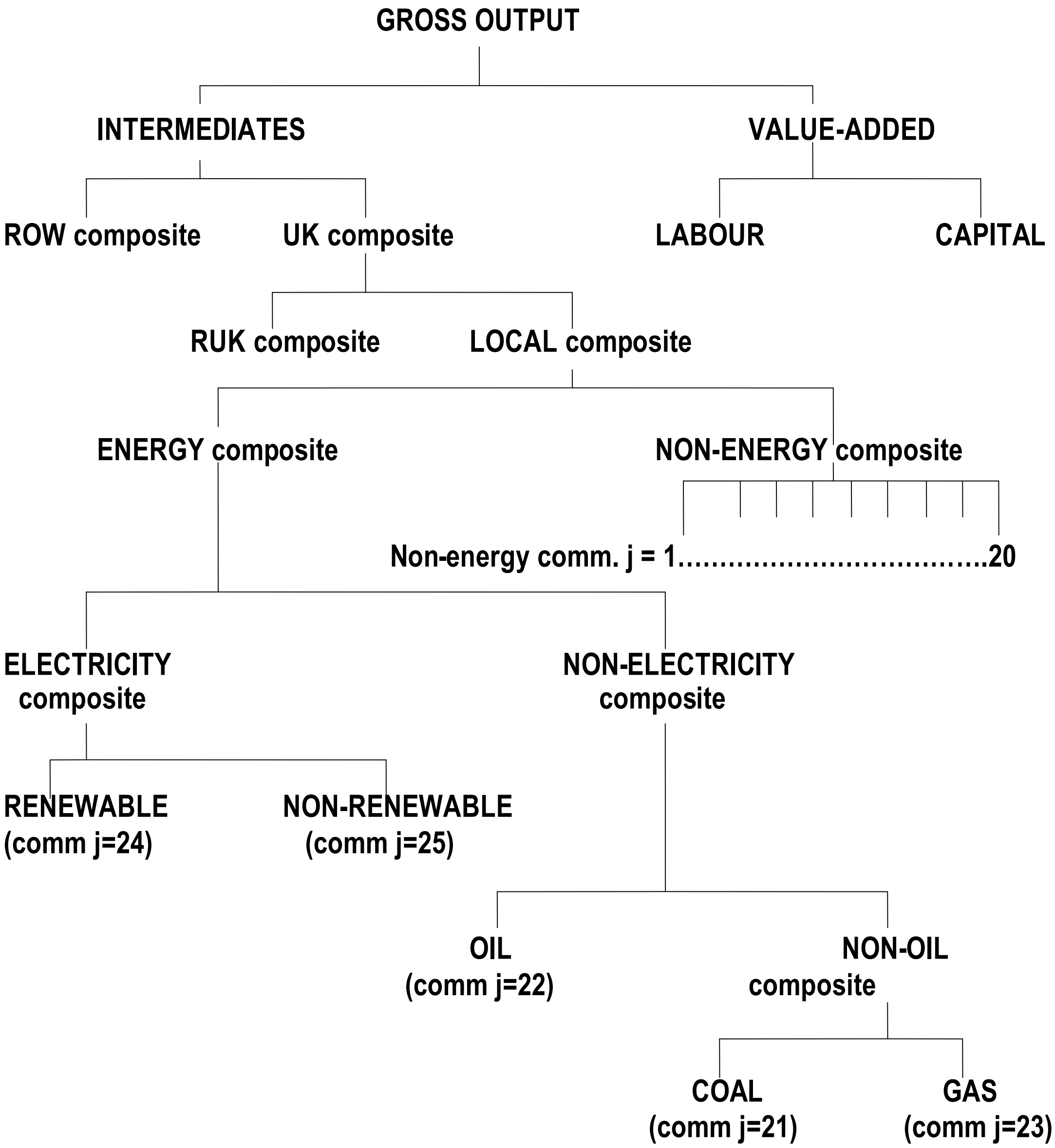
Key results, alternative KLEM elasticities and labour market specifications

% change from base year values

	Scotland				UK	
	Flex/Flex		Flex/Fixed		Flex/Fixed	
	Short run	Long Run	Short Run	Long run	Short run	Long run
0.4	-0.66	-0.30	-0.66	0.48	-1.39	-2.25
	Fall	Fall	Fall	Rise	Fall	Fall
0.8	0.94	1.00	0.94	1.81	0.29	-0.25
	Rise	Rise	Rise	Rise	Rise	Fall
1.1	2.12	2.01	2.12	2.82	1.70	1.29
	Rise	Rise	Rise	Rise	Rise	Rise

Figures

Figure 1. Production structure of each sector i in the 25 sector/commodity AMOSENVI KLEM framework



Note: As in Appendix 1, RUK terms drop out in the case of the UKENVI national model

Figure 2. Impacts on EKC variables of a 5% increase in energy efficiency in all Scottish production sectors - central case scenario (key KLEM elasticities 0.4, Flex/Flex labour market specification)

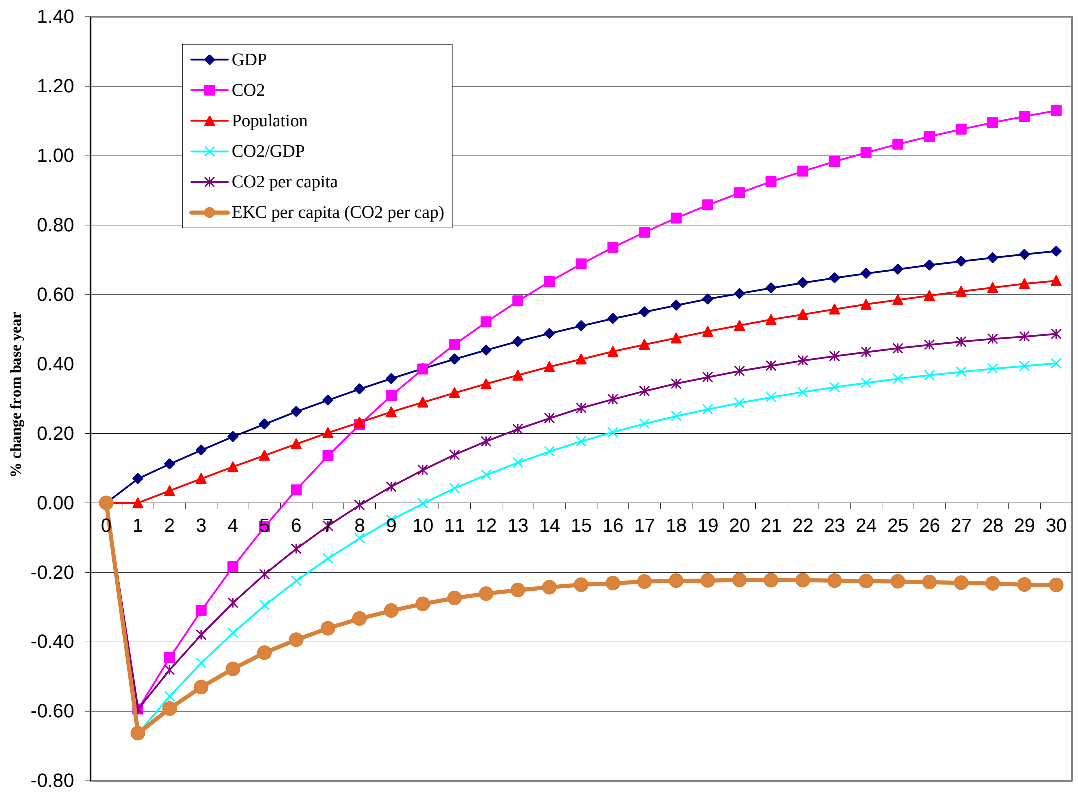


Figure 3. Impacts on real wage, population and EKC per capita of varying the elasticity of substitution of energy for other inputs (Flex/Flex labour market specification)

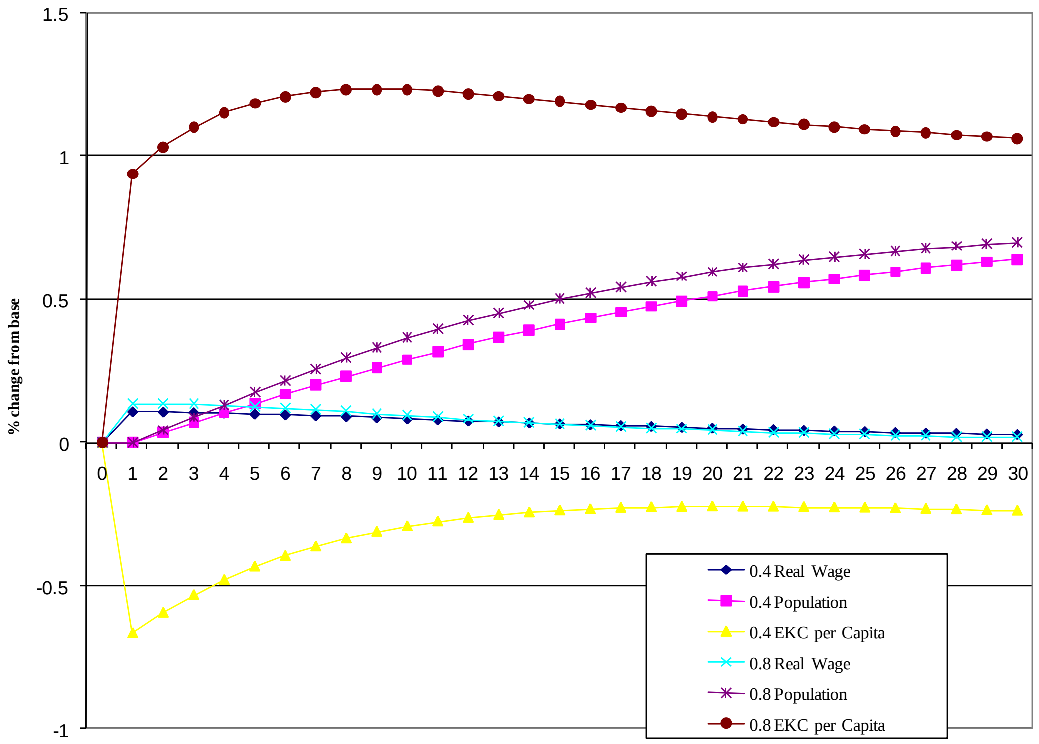


Figure 4. Impacts of redefining EKC per capita in terms of GDP per capita as a measure of growth (central case scenario: key KLEM elasticities 0.4; Flex/Flex labour market specification)