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Do Productivity Improvements Move Us Along the Environmental Kuznets Curve?

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Abstract

The Environmental Kuznets Curve (EKC) hypothesis focuses on the argument that rising prosperity will eventually be accompanied by falling pollution levels as a result of one or more of three factors: (1) structural change in the economy; (2) demand for environmental quality increasing at a more-than-proportional rate; (3) technological progress. Here, we focus on the third of these. In particular, energy efficiency is commonly regarded as a key element of climate policy in terms of achieving reductions in economy-wide CO2 emissions over time. However, a growing literature suggests that improvements in energy efficiency will lead to rebound (or backfire) effects that partially (or wholly) offset energy savings from efficiency improvements. In this paper we consider whether increasing labour productivity will have a more beneficial, or more predictable, impact on CO2/GDP ratios than improvements in energy efficiency. We do this by using CGE models of the Scottish regional and UK national economies to analyse the impacts of a simple 5% exogenous (and costless) increase in energy or labour augmenting technological progress.

Keywords: computable general equilibrium models; technical progress; energy efficiency; labour productivity; environmental kuznets curve

JEL D57, D58, R15, Q41, Q43

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1. Introduction.

The Environmental Kuznets Curve (EKC) has emerged as both an empirical phenomenon, and as a message to politicians. 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 is that promoting economic growth does not have to be seen as being in conflict with a cleaner environment, and indeed that growth will be associated with falling levels of pollution. Finding policies that push an economy along the EKC at a faster rate, or which allow it to "tunnel through" the EKC, thus pays a kind of double dividend.

The standard theoretical argument for why pollution levels can fall as, for example, 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, 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. These technological improvements are somehow correlated with economic growth, although the mechanism relating per-capita GDP growth and, say, energy efficiency, is not well-understood (Bretschger, 2005).

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. The UK government has placed improvements to energy efficiency as a key element of climate policy in terms of achieving reductions in CO_2 emissions over time (UK Climate Change

Committee, 2008). A policy-relevant question is then concerned with the extent to which improvements in the efficiency of input use – their productivity – translate into improvements in the ratio of GDP to CO2 emissions at the level of the economy as a whole. Moving along the EKC towards the turning point implies an improvement (increase) in the GDP/CO2 ratio, but this could also be driven by improvements in the efficiency with which any input to production is used, not just energy. Here, our concern is to compare the relative performance of equivalent improvements in energy and labour, in terms of 'moving along the EKC'. Understanding the relative performance of productivity improvements would help in the formulation of climate change policy, in terms of which kinds of productivity improvements should be encouraged or incentivised the most.

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 rebound (or backfire) effects that partically (or wholly) offset the energy savings from these pure efficiency improvements. This finding is consistent with the growing literature on what are referred to as "rebound" and "backfire" effects (Jevons, 1865; Khazzoom 1980; Brookes 1990; Herring, 1999; Birol and Keppler, 2000; Saunders, 1992, 2000a,b; Schipper, 2000 – see Sorrell, 2007, for a recent review). In our previous work we argue that the occurrence of 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 increases both 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* pollution per unit of GDP. Thus, in looking at the relative effects of improving the productivity of inputs, it is important to control for these general equilibrium effects on output and pollution. To do so we employ a Computable General Equilibrium (CGE) model to carry out the simulations, using the UK and Scottish economies as case studies of economies with quite different economic structures, particularly in terms of the role and openness of local energy supply sectors.

In what follows, Section 2 contains a brief summary of the relevant literature on the EKC, both theoretical and empirical; Section 3 describes the UK and Scottish variants of the AMOSENVI model used in the simulations; Section 4 reports the results of simulations where we increase the efficiency with which energy is used in production; including sensitivity analysis of results to assumptions made about substitution elasticities, migration of labour and which sectors of the economy are targeted with the efficiency improvement. Section 5 reports corresponding results for an increase in labour efficiency. Section 6 concludes, and makes some suggestions for further research.

2. Literature review

Improvements in energy and labour efficiency can change a countries position on EKC, which shows the relationship between a country or region's income per capita and different environmental variables. The EKC hypothesis, which is covered in detail by Stern (1996), suggests that as we increase productivity at the input factor level we would observe a movement along the curve brought about by increases in growth accompanied by, initially, a lower-than-proportional growth in pollution, and then by falling pollution levels. The evidence to support this hypothesis has been explored in the literature and argued to exist with respect to most air pollutants and several water pollutants by estimating on cross-country and time series data (e.g Grossman and Krueger 1994). However, due to issues relating to data and depending on the type of analysis undertaken, such empirical work has been questioned by several authors, such as Stern (1996) and Arrow et al (1995). If the EKC argument holds, then by improving efficiency at input factor level we would be able to pursue policies in favour of economic growth which would also lead to environmental improvements – a double dividend (Stern 1998).

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. In their 1994 study, which looked at four different environmental indicators, they find that in the earlier stages of a country's development there is evidence of environmental deterioration but after a certain turning point, given generally to be $8000 (GDP per capita), there are signs of improvement. Rothman (1998) uses the environmental indicators of clean water, urban sanitation and urban air quality to show improvement with increased income, with or without an initial period of deterioration.

Rothman (1998) also observes that as a country becomes richer we would observe a rise in indicators such as CO2 and municipal waste per capital. More recent empirical contributions include overviews by Norman and Deacon (2006), and findings for biodiversity (MacPherson and Nieswiadomy, 2005)) and for CO2 (Dijkgraff and Vollerbergh, 2005), whilst Barrett and Graddy (2000) analyse the effects of measures of social capital on the EKC.

Authors have presented theoretical models which aim to explain the EKC (see, for example, Lopez, 1994; Stokey, 1998; Andreoni and Levinson, 1998; and Selden and Song, 1995). This literature identifies three main reasons movement along for the EKC, the first being composition and structural changes. This refers to how a country's economic structure changes as it becomes richer and this drives down the level of pollution as it switches to more environmentally friendly industries. Arrow et al (1995), although sceptical about the empirical studies available, argue that the EKC is a natural progression as richer countries move into cleaner industries as opposed to polluting industrial economies. This line of argument is often referred to as the pollution leakage hypothesis which is commonly put forward to explain why the richer countries can become richer as they reduce their levels of pollution. Other authors who support this argument are Stern (1998), Suri and Chapman (1997) and Cole (2004**),** who have presented theoretical papers on the pollution haven hypothesis argument as a reason as to why we observe lower emission levels in developed with as they continue to grow. Brovoll and Foehn (2006) investigated the pollution leakage hypothesis as the main reason why rich countries move along the EKC curve. They showed that by quantifying how a unilateral growth induced policy affects both domestic and foreign emissions the more developed countries seems to lower their own emission levels, although pollution rises elsewhere.

Another driver behind the EKC is the changing political structure of the economy, whereby more advanced countries have more advanced mechanisms in place to encourage environmental policy and in such countries the electorate have more power in persuading those in power to deal with polluting externalities, see Jones and Manuelli (1995) who use an overlapping generations model to examine this argument. This strand of argument also draws on the relationship between rising incomes and an increase in demand for environmental quality, resulting in stricter legislation.

Our analysis, however, focuses on technological progress as a driving force, in particular energy and labour efficiency improvements. 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. This is supported by several authors who find evidence in favour of technical progress, see Anderson and Cavendish (2001) who use a dynamic simulation model to look at PM, SO2 and CO2 in developing countries. Empirical evidence *against* the technology argument as a driver of the EKC 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 CO2 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. Theoretical contributions from Andreoni and Levinson (1998) and Pasche (2002) cite technological and structural change as the reasons why a country can experience positive growth rates whilst experiencing falling GHG emissions. Furthermore, Stern (1996) lists improved technology as one of the reasons to explain why developed countries can observe a reduction in environmental degradation as they continue to grow.

Here we use numerical CGE analyses to consider the likely impact of technological progress on an economy's position on the EKC curve. The use of CGE models to analyse economy-environment is now widespread in the literature (Bergman, 2005, provides the most recent overview of the current 'state of play' in the field). However, applications that model the EKC in a computable equilibrium framework are more limited. For our current purposes, it is therefore instructive to look to other CGE applications that incorporate technology changes.

Technological progress or efficiency improvements have been incorporated into numerous CGE or top down models as an augmenting exogenous coefficient in the production function. (for example, Gerlagh and Van der Zwann, 2003). Other papers incorporate technological change through energy or labour efficiency increases through innovations in R&D (for example, Popp 2004). 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 negative leakage, all of which can be argued to place a country favourably on the EKC curve. For example, 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. 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. In this paper the technological progress is brought into the model by increasing the output level from a set of given inputs, so the production function shifts upwards. Jacoby et al (2006) provide an in depth description for modelling technical change by using the MIT Emissions Prediction and Policy Analysis Model (EPPA). Wing and Eckaus (2007) also use a CGE model to examine the effects of an energy improvement for the US economy. Here, one of the traditional methods of modelling technical progress - assuming some continuing autonomous energy efficiency improvement- is critiqued on the basis that it ignores several important assumptions that would be expected in the long run. For example, an inability to represent inter-sectoral differences for the efficiency improvement may lead to "biased estimates of the future decline in aggregate energy intensity" (Wing and Eckaus, 2007, p.5281).

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, but argue that we should not rely on the theory behind the EKC as a means to solving issues surrounding climate change. Another author who uses a CGE model to analyse the rebound effect theory in an EKC setting is Vickstrom (2004), who 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. Vickstrom argues that improvements in energy efficiency bring about a rebound effect throughout the economy which will in general shift the consumer consumption bundle towards more environmentally friendly products and away from the 'bads'. Johansson and Kristrom (2007) propose a simple general equilibrium model to explain the EKC hypothesis and find that it can be explained in terms of substitution and income effects with technological progress being the main driver. It is important to note that technological progress is treated as exogenous in this model. For other CGE contributions that consider the EKC hypothesis (but without specific focus on technological progress) see Bruvoll et al (2003).

In the next section, we introduce our own CGE models for the Scottish and UK economies, SCOTENVI and UKENVI. However, we would emphasise that these models are at an early stage of development and our intention here is more analytical than empirical in nature (i.e. to try and identify the main causal processes linking changes in technological progress and environmental variables).

3. The SCOTENVI and UKENVI energy-economy CGE models of the Scottish and UK economies

The Scottish and UK models employed here are both variants of the generic AMOSENVI model, the energy-environment variant of the basic AMOS CGE framework developed by Harrigan et al (1991). AMOS is an acronym for A Model of Scotland, deriving its name from the fact the framework was initially calibrated on Scottish data. However, AMOS is a flexible modelling framework, incorporating a wide range of possible model configurations, which can be calibrated for any small open regional or national economy for which an appropriate social accounting matrix (SAM) database exists (for example, in Learmonth et al, 2007, the AMOS framework is applied to the Jersey economy). In previous applications the Scottish model has retained the generic name of AMOSENVI. However, for clarity, here we will refer to the Scottish model as SCOTENVI and the UK model as UKENVI. A condensed description of the AMOSENVI modelling framework is provided in Appendix 1. This section provides a broad overview of the structure of these two models.

3.1 General structure

Both the SCOTENVI and UKENVI models share the some generic characteristics. Each has 3 transactor groups, namely households, corporations, and government; 25 commodities and activities, 5 of which are energy commodities/supply (see Figure 1 and Appendices 2 and 3) for details). The specific sectoral breakdown of the two models (Appendices 2 and 3) has been based on policy priorities and key energy use sectors in Scotland and the UK respectively. However, both models have the same 5 energy supply sectors: coal; oil; gas; renewable and non-renewable electricity. 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 UK is modelled as a small open national economy, with a single exogenous external transactor, ROW.

The generic 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, cost minimisation is imposed in production with multi-level production functions, generally of a CES form but with Leontief and Cobb-Douglas being available as special cases (see Figure 1). 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 in the Scottish case, and ROW in the UK case) are exogenous, but the demand for domestic exports and imports is sensitive to changes in relative prices between (endogenous) domestic and (exogenous) external prices (Armington, 1969). Investment is a little more complex as discussed below in Section 3.3.

3.2 Labour market

A single local labour market is imposed in both models and characterised by perfect sectoral mobility. 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). Here, we parameterise the bargaining function from the 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 (Scottish or UK) real consumption wage and the unemployment rate respectively, t is the time subscript and α is a calibrated parameter.[1] Empirical support for this "wage curve" specification is now widespread, even in a regional context (Blanchflower and Oswald, 1994).

[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.

In some of the simulations endogenous migration is incorporated in the model (i.e. labour can freely migrate from the rest of the UK, RUK, in the Scottish case of the rest of the world, ROW, in the UK case) so that population adjusts between periods (years). Net migration is positively related to the real wage differential and negatively related to the unemployment rate differential between Scotland and RUK or the UK and ROW and 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.

3.3 Capital and investment

Within each period of the multi-period simulations using the SCOTENVI and UKENVI frameworks, both the total capital stock and its sectoral composition are fixed, and commodity markets clear continuously. Each sector's capital stock is updated between periods via a simple capital stock adjustment procedure, according to which investment equals depreciation plus some fraction of the gap between the desired and actual capital stock. 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. 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, 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. 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

Figure 1 summarises the production structure of the generic AMOSENVI framework. 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 combining with capital (e.g. Bergman, 1988, 1990), or within the intermediates nest (e.g. Beauséjour et al, 1995). Given that energy is a produced input, it seems most natural to position it with the other intermediates, and this is the approach we adopt here. However, any particular placing of the energy input in a nested production function restricts the nature of the substitution possibilities between other inputs. The empirical importance of this choice is an issue that requires more detailed research, and is the subject of research in the current research programme of which this paper is part (see Guerra Hernandez and Turner, 2009).[2]

The multi-level production functions in Figure 1 are generally of constant elasticity of substitution (CES) form, so there is input substitution in response to relative price changes, but with Leontief and Cobb-Douglas (CD) available as special cases. In the applications reported below for both Scotland and the UK, Leontief functions are specified at two levels of the hierarchy in each sector – the production of the non-oil composite and the non-energy

[2] Note that there is also debate in the CGE literature regarding the use of nested functional forms because of the imposition of separability assumptions (see Turner, 2002 for a review of this debate). To avoid this problem, Hertel and Mount (1985), Depotakis 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 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), Depotakis 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 materials aggregates on the second level. Thus, even these authors are in fact prepared to accept some separability assumptions. Another activity being undertaken in the current project of which this paper is part involves estimating the structure of the KLEM production function (and parameter values therein) for each sector in the UKENVI model following the approach proposed by Kemfert (1998).

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.

At present, econometric estimates of key parameter values are not available for either the Scottish or UK models (again this is the focus of current research in the wider programme of research of which this paper is part – see Footnote 2). Previous work simulating efficiency improvements using the SCOTENVI and UKENVI models (Hanley et al, 2009, and Allan et al, 2007, respectively) 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 and 5 the Armington trade elasticities are generally set at 2.0, 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, Turner's (2008, 2009) analysis suggests that the key set of parameters in determining whether increased efficiency in the use of a 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 and 5 we set the elasticity of substitution at three key nests in the multi-level production function first at an inelastic value (0.8) then at an elastic one (1.1). 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. At all other nests involving local inputs the default AMOSENVI values (see Allan et al 2007, Hanley et al, 2009) of 0.3, apart from where Leontief functions have been imposed and in the case of the electricity composite, a higher value of 5.0 is imposed (again to reflect the homogeneity of electricity from different sources and consequent higher degree of substitutability).

3.5 Modelling pollution generation

We relate emissions of CO2 to the use of polluting inputs in the form of the different types of fuel use at different levels of the energy composite (locally-supplied energy inputs) in Figure 1. Scottish and UK CO2 emissions from the local combustion of imported energy inputs are captured through the use of fixed input-pollution coefficients at the higher nests where the

RUK and/or ROW composite commodities are determined. 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 UK economy. Corresponding Scottish-specific sectoral emissions data are not currently available, with the important exception of electricity generation. We also attempt to regionalise the UK environmental data by adjusting sectoral emissions to reflect patterns of fuel use in the Scottish input-output accounts for 1999 (Scottish Executive, 2002). 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. 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).

3.6 Databases

The database on which the structural characteristics of the Scottish model are calibrated is a social accounting matrix (SAM) for 1999. The core element of the Scottish SAM is the published Scottish input-output (IO) tables for 1999 (Scottish Executive, 2002). 1999 has been retained as the base year for the SCOTENVI model because the sectoral breakdown of this particular IO database separately identifies sectors of central importance in assessing the likely impact of energy efficiency. This allows us to distinguish among four broad energy types: coal, oil, gas and electricity. In particular, we have been able to draw on experimental data supplied by the input–output team at the Scottish Government to disaggregate the electricity supply sector into the ‘Renewable (hydro and wind)’ and ‘Nonrenewable (coal, nuclear and gas)’ sectors. However, we hope that a more updated variant of this database will be available in future. The reader is referred to Hanley et al (2009) for a more extensive discussion of the SCOTENVI SAM.

The main database for UKENVI is a specially constructed SAM for the UK economy for the year 2000 (constructed by Allan et al, 2006). This required the initial construction of an appropriate UK Input-Output (IO) table since an official UK analytical table has not been published since the 1995 table in 2002 (National Statistics, 2002). A twenty-five sector SAM was then developed for the UK using the estimated IO table as a major input. The sectoral aggregation is chosen to focus on key energy use and supply sectors. The division of the electricity sector between renewable and non-renewable generation used the experimental disaggregation provided for Scotland. This was then adjusted to reflect the different pattern in electricity generation between the UK and Scotland. Full details on the construction of the UK IO table and SAM are provided in Allan et al (2006).

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

In our first set of simulations we consider the impact of increased efficiency in the use of energy in production activities on the EKC. That is, we examine whether technological progress results in increased prosperity (represented by GDP) accompanied by a relative reduction in pollution levels (here represented by emissions of the main greenhouse gas, CO2) where this technological progress takes the form of increased efficiency in the use of energy as an input to production. If GDP rises faster than CO2 emission, this implies that technological change moves the economy *along* the EKC towards a possible turning point, since we have a reduction in the CO2 intensity of GDP. However, to pass the turning point and move onto the downward section of the EKC requires that absolute pollution levels actually fall as GDP rises, (rather than GDP rising faster than CO2). Both effects can be tested for.

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 in both the Scottish and UK models[3]. 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 compared with improvements in the productivity of other inputs. We introduce the energy efficiency shock by increasing the productivity of the

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

energy composite in the production structure of all industries.[4] This is energy-augmenting technical change and the procedure operates exactly as in equation (2) below. If we begin by distinguishing between energy measured in natural or physical units, E, and 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:

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

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 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:

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

where p represents price and the subscript identifies energy in either physical or efficiency 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. In a general equilibrium context:

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

[4] We do not change the efficiency with which energy is used in the household or government consumption, investment, tourism (in the case of Scotland) 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. This is an important limitation (see Turner, 2008) and one that we aim to address in future research.

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 equations (3) and (4) into equation (2), giving:

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

This tells us that the general equilibrium price demand for energy in efficiency units is the driver of what happens to energy consumption (and energy-related emissions).

However, while the simple conceptual approach in equations (2)-(5) 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, as in the cases of Scotland and the UK, energy is often 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 (4).

The second problem is that of identifying of the general equilibrium elasticity of demand for energy, η, in (4) and (5), 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 (2008) 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) 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.

In this paper, while we employ numerical general equilibrium models of the Scottish and UK economies, in empirical terms these models are at an early stage of development and the shocks we introduce highly simplified. Our analysis is intended to provided an analytical contribution using numerical models in order to consider the type of impacts we may expect to see under several key assumptions regarding the determination of general equilibrium price elasticities of demand in response to changing input prices, and the impacts of targeting efficiency improvements at different types of activities in differently structured economies. For example, the output of the five Scottish energy supply sectors (in our base year of 1999) equates to 4.2% of total Scottish production and these exports from these sectors directly account for 4% of total Scottish exports. In the UK (for our base year of 2000), the corresponding figures are 3.5% and 1.9% respectively. Therefore, the importance of energy supply activities is quite different across the two economies that we model. Energy supply activities tend to be relatively energy-intensive so efficiency improvements aimed at these sectors are likely to induce larger rebound effects than those aimed at non-energy-supply sectors. For example, Hanley et al (2009) find that huge backfire effects (where there is a net increase in total energy consumption in response to an efficiency improvement) observed when energy-augmenting technological progress is improved in all Scottish production sectors disappear when energy supply sectors are not targeted.

We confine our attention to a limited number of issues of interest – i.e. production elasticities and sectors targeted with the shock, as well as the impact of allowing total labour supply to adjust through migration - in order to clearly understand the impacts of each of these on simulation results. We identify four cases, where we vary our assumptions regarding each of these in turn:

Case EA1 – the 5% increase in (exogenous) energy-augmenting technological progress is introduced to all 25 production sectors of each the Scottish and UK economies with the three key KLEM production elasticities identified in Section 3.4 (capital-labour, energy-non energy intermediates and total intermediates-value-added) set at a price inelastic (<1) value of 0.8. Within this we present results where the labour supply can adjust through migration, and then where it cannot. The ability of the economy to adjust in response to a positive supply shock (such as an efficiency improvement) will depend on whether any constraints on factors of production are present. In all cases, capital can adjust over time through investment (as detailed in Section 3.3); we vary the adjustment of population/labour supply (as detailed in

Section 3.2) because this is interesting in comparing the results of our energy efficiency shocks with the labour efficiency ones (Section 5) as labour is the input targeted with the improvement in technological progress.

Case EA2 – as case EA1, but with the value of KLEM production elasticities raised to a price elastic (>1) value of 1.1. If the elasticity of substitution in production is indeed a dominant parameter in the determination of the general equilibrium price elasticity of demand for energy, this should increase the magnitude of rebound effects towards backfire (increased energy consumption) in response to the energy efficiency improvement.

Case EA3 – as case EA1, but with the efficiency shock limited to the 20 non-energy-supply sectors (sectors 1-20 in Appendices 2 and 3)

Case EA4 – as Case EA3 but with the value of KLEM production elasticities raised to a price elastic (>1) value of 1.1 (as in case EA2 relative to EA1).

There are a number of different underlying effects that determine and magnitude and direction of changes in energy consumption (and, consequently, rebound effects) in response to changes in energy consumption. Turner (2009) characterizes these as follows:

(i) **The pure engineering or efficiency effect** – demand for energy is reduced as less physical energy inputs are required to produce any given level of output (effect entirely focussed on the input targeted with the efficiency improvement);

(ii) **The substitution effect** as demand for energy increases as the price of energy falls relative to other input prices (positive effect on the input targeted with the efficiency improvement, negative effect on substitute inputs);

(iii) **The composition effect** in output choice at the aggregate level as relatively energy-intensive products benefit more from the fall in effective and/or actual energy prices price (however, this will also pull up other input use in so far as inputs other than energy are used by energy-intensive sectors);

(iv) **The output/competitiveness effect** resulting from the fall in supply price of commodities that (directly and/or indirectly) use energy as an input to production (as in (iii), there will be indirect positive impacts on other inputs used in production of these commodities);

(v) **The income effect** resulting from increased real household incomes, which will impact on household consumption of all commodities, including the direct and/or indirect consumption of energy (so, again, positive impact on use of all inputs).

(vi) **The disinvestment effect**, which may occur in domestic energy supply sectors if direct and derived demands for energy are not sufficiently elastic to prevent falling energy prices leading to a decline in revenue, profitability and the return on capital in these sectors. The disinvestment effect constrains the elasticity of supply of energy, putting upward pressure on the actual price of energy and downward pressure on the demand for energy (and other inputs to production in energy supply sectors).

It is important to note from this listing that the efficiency effect (i) is the only one that has an entirely negative effect on the input targeted with the productivity improvement, in this case energy use, alone, and the substitution effect (ii) is the only one that has an entirely positive effect on the targeted input and an entirely negative one on other inputs. Effects (iii)-(v) will all also have some positive impact on locally supplied inputs not targeted with the efficiency improvement (and, in most cases, also on imports).[5] This becomes particularly important in considering the relative impacts of a labour efficiency improvement in Section 5.

4.2 Energy efficiency simulation results

If we take case EA1 first (key production parameters inelastic, all 25 sectors targeted with the energy efficiency improvement), Table 1 reports the impacts on key aggregate variables under alternative assumptions regarding migration of labour for the UK and Scotland respectively. As noted above, the efficiency change is introduced costlessly. 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. The short and long run time periods in Table 1

[5] Turner (2008) shows that in some (extreme) cases, very low price elasticities of export demand may actually lead to an efficiency improvement manifesting as a negative supply shock (due to negative terms of trade effects) so that there are negative competitiveness and income effects reducing the use of one of more factors of production) and commodity use by households. In terms of imports, the substitution effect will be negative (as local prices fall) but positive output/competitiveness and income effects will increase demand for both local and imported inputs/commodities.

are conceptual time periods. 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, in the third and sixth columns (labelled 'Migration' for the UK and Scotland respectively), where migration from the rest of the UK in the Scottish case and from ROW in the UK case occurs endogenously, population stocks also. In terms of the economic results, the main point to note is that the long-run stimulus is smaller with no migration. The main underlying factor is that, without migration (labelled 'No migration' in the 2nd and 5th columns of Table 1), real wages do not adjust back to their base year levels in the long run, with a sustained increase in nominal wages. This limits the competitiveness of the economy and, therefore, the effects of the positive supply shock. Migration also puts upward pressure on energy consumption, both through the greater expansion of production activity, but also from the increased number of households.

Where we run the model in period-by-period mode with the gradual updating of population and capital stocks, a close adjustment to the long run values will often take a number of years. In the case of the UK, for this particular shock, the model begins to converge on long-run values after around 70 years, but in the case of Scotland, it takes much longer. Indeed after 150 years, convergence is very close but not entirely complete on all variables. This is due to the much greater stimulus to the Scottish economy from this shock given the greater importance of the energy supply sectors, as explained above.

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 UK economic activity that is generally greater in the long run than in the short run. For case EA1 (Table 1), in the long run without migration there is an increase of 0.17% in GDP, 0.19% in employment and 0.30% in exports. The expansion is generally lower in the short run, where GDP increases by 0.12%, but there is a larger increase in consumption (0.36%) and employment (0.22%) in the short run than in the long-run (0.34% and 0.19%). However, if we allow migration in response to rising real wage rates and falling unemployment, the third column of Table 1 shows that there is a bigger expansion in all variables in the long-run, except wages which are driven back to their initial real level as the economy adjusts to a new equilibrium. In both the migration on and off cases, there is a drop in imports in both the short and long run. The net effect on imports depends on the strength of the relative price effect (as UK 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 UK demand for all local and imported commodities). In the first three columns of Table 1 the former effect dominates and imports decrease (by 0.23% in the short run, by 0.19% in the long-run without migration, and by slightly less, 0.16%, with the larger expansion when migration is present.

In terms of energy use and the CO2 intensity of GDP, in the short run for the UK case EA1 (Table 1 and Figure 3), there is a drop in total (economy-wide) electricity consumption of 0.14%. However, this is less than proportionate to the energy saving that would be implied by the 5% efficiency improvement– i.e. there is a rebound effect in energy use.[6] In the case of non-electricity energy consumption (coal, oil and gas), there is an immediate backfire effect, with total (economy-wide) consumption of UK supplied energy (the sub-set affected by the shock) rising by 0.34%. In terms of the level of CO2 emissions, there is a net increase of 0.41% (reflecting the initial mix of different types of energy use) and this increase in CO2 emissions is greater than the short-run growth in GDP (0.12%) so that there is a net increase in the CO2-intensity of UK GDP of 0.29%. This suggests that the economy is moved onto the *upward* section of the EKC curve. However, the long-run direction of effects is quite different and the net effect depends crucially on whether migration of labour to the UK is possible. With no migration (second column of Table 1; also see Figure 2), the long-run drop in electricity consumption, -0.45%, is larger than in the short-run (giving smaller rebound effects over the long-run – due to a disinvestment effect in the electricity supply sectors, identified by Turner, 2008, 2009). In the case of non-electricity energy, the short-run increase is quickly reversed (see Figure 1), leading to a long-run drop in consumption of 0.02%. CO2 emissions of 0.08%, which, taken with the 0.17% increase in GDP, gives us a drop in the CO2-intensity of GDP of 0.25%. With falling CO2 emissions, this would move the economy from the upward section of the EKC in the short-run to the downward section in the long-run. However, if we allow migration, the third column of Table 1 and Figure 2 show us that

[6] Where only a subset of energy uses are targeted with the efficiency improvement (here use of domestically supplied energy in the production sectors of the economy), this must be taken into account in calculating the rebound effect (see Turner, 2008, 2009). For example, in case EA1, where all 25 production sectors are targeted, 69.2% of UK electricity use is affected, with the implication that zero rebound (i.e. a decrease in energy use that is proportionate to the efficiency improvement) would equate to a 3.46% reduction in total electricity use in the UK, rather than 5%.

energy consumption actually grows over time, leading to a long-run increase in CO2 emissions of 0.85% (compared to 0.41% in the short-run). However, the growth in CO2 emissions is overtaken by the growth in GDP (1.04% in the long run with migration) so that the CO2 intensity of GDP falls by 0.19% over the long-run. This implies that while the economy would move along the EKC after the short-run (the first period after the shock is introduced), allowing migration of labour is sufficient to stop it from moving onto the downward section over the longer run. Figure 3 shows that, for this model configuration and shock, the qualitative adjustment to the long run direction of results for the CO2 intensity of GDP occurs fairly rapidly.

Columns 4-5 in Table 1 show that the UK results are in contrast with the Scottish case. Here the short-run stimulus to GDP, employment, real wages and consumption is proportionately smaller than in the UK, but there is an immediate increase in exports. Note also that the proportionate increase in aggregate investment demand is greater in Scotland (the disinvestment effects – Turner, 2008, 2009 - in the energy supply sectors observed for the UK do not occur in Scotland for this model configuration and shock). However, in the long run (or after 150 periods), column 5 of Table 1 shows us that, even where no migration occurs, all of the positive effects of the increase in energy efficiency are greater than in the UK case. Column 6 shows us that where migration occurs the economic impacts are even larger. However, with respect to energy consumption, the greater importance of energy supply activities in the Scottish economy (see above), combined with the energy- and export-intensity of these sectors, means that (for this model configuration), backfire effects are observed from the short run into the long run, whether migration is on or off. However, the expansion in energy use and, consequently, CO2 emissions is greater with migration (allowing a larger economic expansion in general, with more households, which directly consume energy). The rise in CO2 emissions is, in all cases, larger than the increase in GDP, so that, reading across the 4th, 5th and 6th columns of Table 1, we see that the CO2 intensity of GDP increases from the short-run, with a larger increase where we have migration. Thus, for this shock (all 25 production sectors targeted) and model configuration (key elasticities of substitution in production set at 0.8), the Scottish economy is on the *upward* portion of the EKC, with its position becoming more negative over time and if we allow a greater flexibility in the adjustment of the economy by allowing migration in response to rising real wages and falling unemployment rates.

Therefore, in comparing the results for the UK and Scotland for case EA1 in Table 1, the first conclusion that we can draw is that the structure of the economy will be important in determining the position on the EKC following an increase in technological progress, and that the migration of labour has important qualitative and quantitative effect (particularly in the UK case).

We subject these results to further sensitivity analysis in terms of which sectors are shocked and the value of key elasticity of substitution parameters in cases EA2 (all 25 sectors shocked, but with a greater degree of substitutability between energy and other inputs, with key substitution parameters set at 1.1) and cases EA3 and EA4 (as EA1 and EA 2 respectively, but targeting only the 20 non-energy-supply sectors with the shock). Tables 2, 3 and 4 show the corresponding results (relative to Table 1 for case EA1) for key economic and environmental variables for cases EA2, EA3 and EA4 respectively. Table 5 summarises the key results (CO2 intensity of GDP and whether CO2 levels rise or fall) in terms of the position of the Scottish and UK economies on the EKC for each case.

What these sensitivity results show us, is that for the UK, where we have *inelastic* parameters and no migration (i.e. cases EA1 and EA3 in Tables 1 and 3 where the key parameters – substitution between energy and materials, capital and labour, and value-added and intermediates in Figure 1 – are set to 0/8), we *can* get the desired effect over time, with CO2/GDP falling and also CO2 levels falling. However, if we allow migration CO2/GDP will fall, but with rising CO2 levels, so that the economy is only moving along the EKC. Which sectors shocked are shocked is also important. If energy supply sectors are not directly targeted with the efficiency improvement, we get a slightly smaller economic boost, but in the short-run CO2 emissions fall with CO2/GDP. However, we still get a long-run backfire effect in energy consumption and a rise in CO2 emissions, but this is much smaller (0.14%) than where all 25 sectors are targeted (0.85%).

In terms of whether energy consumption rises rather than falls, the key issue for the UK is whether the key elasticities of substitution in production are elastic or inelastic. Turner (2008, 2009) shows that production elasticities dominate in determining the general equilibrium price elasticity of demand for energy in the UK to the extent that, if these are set above 1, backfire effects will be observed. Tables 2, 4 and 5 show that raising the value of the key elasticities of substitution in production from 0.8 to 1.1 is alone sufficient to give us increased

CO_2 emissions and CO_2/GDP in all time periods and shock configurations (i.e. whether 20 or 25 sectors are targeted with the efficiency improvement). These negative environmental effects are smaller if the five energy supply sectors are not shocked (case EA4), as are the economic benefits; however, in all cases with elastic parameters, the improvement in energy augmenting technological progress puts the UK economy on the *upward* section of the EKC.

Reading down the list of different effects driving changes in energy consumption in response to improved energy efficiency in Section 4.1, an obvious explanation for the difference in results when the key elasticities of substitution in production are increased is the strength of substitution effects in favour of energy over other inputs to production. However, if we examine the increase in the impact on economic variables between cases EA1 and EA2 (Tables 1 and 2) and EA3 and EA4 (Tables 3 and 4) we can see that the strength of output/competitiveness and income effects is also slightly greater when substitution elasticities are increased (i.e. the economy is better able to respond to the efficiency improvement in general).

The Scottish results in each case follow the same pattern, except case EA3, where only the 20 non-energy-supply sectors are targeted with the key elasticities of substitution in production set at 0.8 (inelastic). In this case we actually get the desired effect in terms of CO_2 levels falling along with CO_2/GDP in both the short and long run and whether migration is on or off (though note that underlying the very small, 0.01 percentage point, difference in the long-run migration on and off results in case EA3 is a much bigger increase in GDP and much smaller reduction in CO_2 levels when migration is possible). However, in short, the one difference relative to the UK case is that in removing the energy-intensive and heavily traded energy supply sectors from the simulation is sufficient to put the Scottish economy on the downward section of the EKC in case EA3 (in contrast to case EA1, where it is on the upward portion). Nonetheless, comparing cases EA3 and EA4 shows that, if the key elasticities of substitution in production are actually elastic, the economy would again be on the upward portion of the EKC as a result of the improvement in energy augmenting technological progress even where only the non-energy supply sectors are targetted.

Therefore in summary, we can say that an improvement in energy augmenting technological progress may place the economy at a variety of points on the EKC curve, depending on: (1)

which activities are targeted with the efficiency improvement; (2) the strength of elasticities in substitution; (3) whether the labour supply is able to expand through migration.

5. Simulating the impacts of increased labour efficiency on the CO2 intensity of GDP

The simulation results in Section 4.1 suggest that the impact of energy-augmenting technological progress on an economy's position on the EKC is somewhat ambiguous and dependent on a number of factors, including the target of the shock, whether the labour supply is able to expand through migration, and the value of elasticities of substitution between factors of/inputs to production. A number of other factors may also have an impact, both in terms of specifications that are currently possible within the SCOTENVI and UKENVI model (but are outwith the scope of the current paper), and on 'real life' policy factors, such as the costs and method of introducing efficiency improvements (which cannot currently be simulated effectively). However, the complexity of the results presented so far are evidence of the argument that it is better to start by understanding the basic drivers of changes in factor use in a general equilibrium context, and then introduce additional layers of sophistication to simulations in a gradual and progressive programme of research.

Here, our second set of simulations attempt to examine the question of whether increasing the efficiency of one of the other factors of production have a more beneficial, or even simply more predictable, impact on CO2/GDP ratios, compared to improvements in energy efficiency. We focus on improvements in labour productivity, as this is a common focus of existing policy on economic development and employment (e.g. Scottish Government, 2007, BERR, 2008).

5.1 Simulation strategy and theoretical considerations

As in the case of energy efficiency in Section 4, we introduce a very simple and illustrative 5% exogenous (and costless) increase in labour efficiency to all production sectors in both the UK and Scottish models. This is introduced by increasing the productivity of the labour input in the production structure in Figure 1 for all industries. This is labour-augmenting technological progress and the procedure operations exactly as shown for energy in equations (2)-(5) in Section 4.1, this time with the general equilibrium price elasticity of demand for *labour* being the key variable driving what happens to the employment of labour. We again identify four cases, LA1-LA4, which are analogous to cases EA1-EA4 in terms of the sectors targeted with the shock (either all 25 or 20 excluding the 5 energy supply sectors), and the values attached to the 3 key elasticities of substitution (between labour and capital, energy and materials, and value-added and intermediates in Figure 1).

The same 5 underlying effects identified in Section 4.1 will drive the results of the labour efficiency simulations: the pure efficiency effect, the substitution effect, the composition effect, the output/competitiveness effect, the income effect. This time the efficiency effect will act to reduce labour demand while the substitution effect will increase the use of labour relative to other inputs (i.e. substitute away from other inputs in favour of labour as the relative price of labour falls). However, the composition, output/competitiveness and income effects will act to boost inputs other than labour (including energy) in so far as labour using sectors also employ other inputs to production. The disinvestment effect will be somewhat different, as labour is not a produced input. However, if the returns on labour fall, we would expect to see out-migration (running down of population stocks).

5.2 Labour efficiency simulation results

If we take case LA 1 first (key production parameters inelastic, 0.8, all 25 sectors targeted with the labour efficiency improvement), the first thing to note in Table 6 is that the economic impacts of this efficiency improvement are greater than observed in case EA1.[7] This reflects the fact that labour is a much more important input to production than energy – in both Scotland and the UK (for our base years of 1999 and 2000 respectively), payments to labour services account for just under 30% of the total input requirement at the aggregate level, while energy purchases only account for about 2%. Therefore, a 5% boost in labour efficiency would be expected to have much bigger impacts than the same proportionate improvement in energy efficiency. However, our core focus here is on the impact of each type of productivity improvement on the CO2/GDP ratio, and in comparing the magnitude of effects on other variables we should compare across cases EA1-EA4 or LA1-LA4.

[7] The long-run effects with migration are also significantly larger in the UK. This is due to the fact that in the Scottish case total labour supply is constrained at the national (UK) level, whereas in the UK case the pool of migrant labour is drawn from the world economy.

However, again, in case LA1 (and the other cases LA2-LA4 in Tables 7-9), with a positive supply-side shock and wage determination characterised by a bargained wage curve, we observe increased GDP, consumption, investment and employment, with reduced unemployment and increased real wages. However, note that nominal wage rates fall, as labour becomes more productive and there is initially a reduced demand for labour as a result of the efficiency effect. However, Table 6 shows that from the outset the efficiency effect is dominated by the other effects identified above, which all act to increase the demand for labour and employment rises even in the short run in both Scotland and the UK. Where migration is possible, the long-run expansion is much bigger. The more elastic the production parameters (comparing cases LA1 and LA2 in Tables 6 and 7, and LA3 and LA4 in Tables 8 and 9), the easer it is for the economy to expand in response to the efficiency improvement and the economic impacts are bigger in both the short-run. The more sectors are targeted with the efficiency improvement (i.e. comparing cases LA1 and LA3 in Tables 6 and 8, and LA2 and LA4 in Tables 7 and 9), the greater the positive economic effects.

However, our main interest here is in the environmental effects of this improvement in technological progress. The results for each case in Tables 6-9 and the summary EKC results in Table 10 suggests that the qualitative impact (i.e. direction of impacts on CO2/GDP and CO2 levels) of the labour efficiency improvement is much less ambiguous than in the case of energy efficiency. We would expect to see substitution effects working in favour of labour and reducing energy use. However, the output/competitiveness effects and income effect act to boost the use of all inputs to production (with the net impact on imports depending on the relative price effect, which reduces imports, and the general stimulus to activity, which increases imports), including energy. In all cases, Tables 6-9 show us that for Scotland and UK, we get rising energy use and CO2 emissions in response to the labour efficiency improvement in both the short and long run. However, in most cases GDP rises faster so that the CO2 intensity of GDP falls and the economy moves along (but not down) the EKC. The one exception is where we allow migration in the UK case. In the long-run with migration CO2 growth overtakes GDP growth and we get increased CO2/GDP (so that we are on the upward portion of the EKC curve. This is because, with migration, the economy pulls in more labour resulting in bigger positive economic impacts but also bigger long run increases in energy consumption. In all of the UK simulations where we have migration, this effect begins to outstrip GDP growth.[8] See Figure 4 for the example of Case LA1, where CO2 emissions start to grow faster than GDP after around 7 years. This change in the direction of effect is slower to happen the more elastic are the key elasticities of substitution in production (as it becomes easier to substitute away from energy in favour of labour). If we look at the case where we have more elastic substitution in production (again with 25 sectors, case LA2), Table 7 shows us that we get slower growth in energy use and faster growth in employment as it becomes easer to substitute towards labour. Also we observe faster growth in GDP as it becomes easier to substitute in favour of the factor where productivity is improved. The same is true for Scotland (though here CO2 growth doesn't actually overtake GDP in the cases examined here, though it may if we reduce the elasticity of substitution in production further and/or increase the responsiveness of labour supply through migration.

Next, we consider the cases where the labour efficiency improvement is confined the 20 non-energy supply sectors (cases LA3 and LA4 in Tables 8 and 9). If we move from case LA1 (Table 6) to LA3, we get smaller increases for both economic and energy and CO2 variables because we have a more limited shock. However, we observe (for both Scotland and the UK) a bigger fall in CO2/GDP when the energy supply sectors are not targeted with labour efficiency improvement (while this is not an energy efficiency improvement, it is still boosting the most energy-intensive sectors in case LA1).

When we move from LA3 to LA4 (inelastic to elastic production parameters for the 20 sector shock), again, for both Scotland and the UK, it is easier to sub towards labour so we observe bigger growth in GDP and employment than in energy use. We also observe bigger drops in CO2/GDP intensity when it is easer to substitute towards labour (and have a smaller rise in the UK case LA4 with migration on). However, underlying this result are bigger GDP increases in both the short and long run (except where we have no migration), and CO2 growth that is bigger in the short run but smaller in the long run.

Generally, labour efficiency reduces CO2 emissions per unit of GDP except in the UK when we allow inward migration. The positive EKC effect grows if we do not boost the energy intensive energy supply sectors (so that there are less negative environmental effects from the

[8] However, note from Footnote 7 that migration effects are much greater in the UK case under our current model specification. In reality, migration is constrained at the national UK level so that the flow migration in response to changing relative wage and unemployment rates modelled here is unlikely to occur smoothly. Thus, our 'migration on' results should be interpreted as an extreme case.

positive output/competitiveness effects) and the more elastic production parameters are (as this allows a bigger substitution effect in favour of labour and away from energy).

6. Conclusions and directions for future research

In this paper we examine the conditions under which increased efficiency in the use of energy and labour as inputs to production in different sectors of the UK and Scottish economies are likely to place the economy at different points on the EKC. This also allows us to quantify the impacts on aggregate CO2 emissions of a policy to improve either labour or energy productivity. We find that in the case of both Scotland and the UK, improved labour efficiency generally reduces the CO2 intensity of GDP, but with increased CO2 levels (due to positive output/competitiveness effects), so that the economy is moving *along* the EKC. In other words, boosting labour productivity will not, in its own, move the economy past a turning point. However, the higher the general equilibrium price elasticity of demand for labour, the greater the reduction in the CO2 intensity of GDP and the faster we move along the EKC (due to positive substitution effects in favour of labour over energy).

However, the results are more complex in the case of energy efficiency. For both our Scottish and UK case studies, 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, but this will depend on which production sectors are directly affected by the efficiency improvement, and on the structure of the economy (in particular, the heavier trade in energy in the Scottish case tends to increase the strength of rebound effects), as well as the time period under consideration. Also important is whether the labour supply can adjust through migration (in the UK simulations reported here, the increase in emissions as a result of in-migration is sufficient to outstrip the growth in GDP and move the economy back onto the upward portion of the EKC). 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.

Thus, our main conclusion is that identification of the key factors influencing the general equilibrium price elasticity of demand for energy and other factors of production, and the quantification of these elements is crucial to inform policy on using energy efficiency improvements as a means of achieving GDP growth with reduced CO2 emissions, or pushing us along the EKC. One element of the work reported here that definitely requires further research input is to try and better quantify the key substitution parameters in production that that have been shown to be so crucial in the results reported here. For example, we are currently engaged in work following the approach of Kemfert (1998) to estimate sectoral KLEM production functions (both specification and parameterisation). However, we also aim to develop the UK and Scottish models to address a number of issues, including more policy-relevant and realistic methods (and costs) of introducing efficiency improvements, and also to examine increased energy efficiency in the household sector. Finally, 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 production accounting measures 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) and others as a possible explanation as to why richer countries can become richer while reducing pollution levels.

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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	$Y = \Psi_n N w_n (1 - t_n) + \Psi_k \sum_i w_{k,i}(1 - t_k) + \bar{\bar{T}}$
(15) Commodity demand	$Q_i = C_i + I_i + G_i + X_i + R_i$

(16) Consumption Demand	$C_i = C_i\left(pq_i, \overline{pq}_i^{RUK}, \overline{pq}_i^{ROW}, Y, cpi\right)$
(17) Investment Demand	$I_i = I_i\left(pq_i, \overline{pq}_i^{RUK}, \overline{pq}_i^{ROW}, \sum_i b_{i,j} I_j^d\right)$ $I_j^d = h_j\left(K_j^d - K_j\right)$
(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 Scotenvi and UKENVI, see Appendices 2 and 3.)

Transactors

RUK = Rest of the UK (Scotenvi only), ROW = Rest of World (Scotenvi 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
$\mathbf{t_n, t_k}$	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 SCOTENVI 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 and articles in concrete, plaster and cement and 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. Case EA1: Impacts (% Change from base year values) of a 5% increase in exogenous energy-augmenting technological progress applied to all 25 production sectors in the UK and Scottish economies - key KLEM production parameters (0.8)

	UK			Scotland		
	Short run	Long run		Short run	Long run	
		No migration	Migration		No migration	Migration
GDP (income measure)	0.12	0.17	1.04	0.09	0.38	0.83
Consumption	0.36	0.34	1.10	0.23	0.42	0.76
Investment	0.03	0.16	0.93	0.61	0.57	0.96
Exports	0.11	0.30	1.14	0.32	0.63	0.97
Imports	-0.23	-0.19	-0.16	0.16	0.20	0.29
Nominal before-tax wage	0.00	0.01	-0.69	0.13	0.17	-0.22
Real T-H consumption wage	0.32	0.28	0.00	0.14	0.26	0.00
Consumer price index	-0.32	-0.27	-0.69	0.00	-0.09	-0.22
Total employment (000's):	0.22	0.19	1.13	0.14	0.27	0.77
Unemployment rate (%)	-2.79	-2.44	0.00	-1.19	-2.26	0.00
Total population (000's)	0.00	0.00	1.13	0.00	0.00	0.77
Total electricity consumption	-0.14	-0.45	0.46	1.27	2.67	3.22
Total non-electricity energy consumption	0.34	-0.02	0.91	0.83	1.87	2.30
Total CO2 Generation	0.41	-0.08	0.85	1.03	2.19	2.63
CO2 Intensity of GDP (CO2/GDP)	0.29	-0.25	-0.19	0.94	1.81	1.78

Table 2. Case EA2: Impacts (% Change from base year values) of a 5% increase in exogenous energy-augmenting technological progress applied to all 25 production sectors in the UK and Scottish economies - key KLEM production parameters (1.1)

	UK			Scotland		
	Short run	Long run		Short run	Long run	
		No migration	Migration		No migration	Migration
GDP (income measure)	0.12	0.17	1.02	0.10	0.37	0.81
Consumption	0.36	0.34	1.09	0.24	0.40	0.74
Investment	0.01	0.16	0.86	0.76	0.58	0.92
Exports	0.16	0.34	1.15	0.37	0.66	0.98
Imports	-0.24	-0.19	-0.18	0.22	0.22	0.30
Nominal before-tax wage	-0.03	-0.03	-0.70	0.13	0.14	-0.22
Real T-H consumption wage	0.32	0.27	0.00	0.15	0.24	0.00
Consumer price index	-0.35	-0.30	-0.70	-0.01	-0.10	-0.22
Total employment (000's):	0.23	0.19	1.14	0.15	0.25	0.75
Unemployment rate (%)	-2.82	-2.35	0.00	-1.27	-2.08	0.00
Total population (000's)	0.00	0.00	1.14	0.00	0.00	0.75
Total electricity consumption	1.38	1.23	2.10	2.79	3.99	4.50
Total non-electricity energy consumption	1.50	1.23	2.13	1.95	2.82	3.21
Total CO2 Generation	1.83	1.46	2.37	2.22	3.20	3.60
CO2 Intensity of GDP (CO2/GDP)	1.70	1.29	1.33	2.12	2.82	2.77

Table 3. Case EA3: Impacts (% Change from base year values) of a 5% increase in exogenous energy-augmenting technological progress applied to the 20 energy use sectors in the UK and Scottish economies - key KLEM production parameters (0.8)

	UK			Scotland		
	Short run	Long run		Short run	Long run	
		No migration	Migration		No migration	Migration
GDP (income measure)	0.04	0.11	0.47	0.04	0.12	0.26
Consumption	0.12	0.15	0.48	0.10	0.13	0.25
Investment	0.17	0.16	0.48	0.24	0.17	0.29
Exports	0.14	0.24	0.59	0.09	0.16	0.28
Imports	0.00	-0.06	-0.05	-0.01	-0.03	0.00
Nominal before-tax wage	0.05	0.03	-0.26	0.02	0.02	-0.11
Real T-H consumption wage	0.09	0.12	0.00	0.06	0.09	0.00
Consumer price index	-0.03	-0.09	-0.26	-0.03	-0.07	-0.11
Total employment (000's):	0.06	0.08	0.48	0.06	0.09	0.25
Unemployment rate (%)	-0.77	-1.05	0.00	-0.50	-0.75	0.00
Total population (000's)	0.00	0.00	0.48	0.00	0.00	0.25
Total electricity consumption	-0.29	-0.24	0.14	-0.23	-0.19	-0.02
Total non-electricity energy consumption	-0.24	-0.19	0.20	-0.18	-0.15	-0.02
Total CO2 Generation	-0.30	-0.25	0.14	-0.18	-0.15	-0.02
CO2 Intensity of GDP (CO2/GDP)	-0.33	-0.36	-0.33	-0.22	-0.27	-0.28

Table 4. Case EA4: Impacts (% Change from base year values) of a 5% increase in exogenous energy-augmenting technological progress applied to the 20 energy use sectors in the UK and Scottish economies - key KLEM production parameters (1.1)

	UK			Scotland		
	Short run	Long run		Short run	Long run	
		No migration	Migration		No migration	Migration
GDP (income measure)	0.04	0.12	0.46	0.03	0.11	0.24
Consumption	0.12	0.16	0.46	0.09	0.12	0.22
Investment	0.27	0.19	0.47	0.28	0.18	0.28
Exports	0.15	0.27	0.60	0.11	0.19	0.28
Imports	0.05	0.00	-0.04	0.00	-0.02	0.00
Nominal before-tax wage	0.04	0.01	-0.26	0.00	0.00	-0.11
Real T-H consumption wage	0.08	0.11	0.00	0.05	0.07	0.00
Consumer price index	-0.04	-0.10	-0.26	-0.05	-0.07	-0.11
Total employment (000's):	0.05	0.08	0.46	0.05	0.07	0.22
Unemployment rate (%)	-0.68	-0.96	0.00	-0.42	-0.62	0.00
Total population (000's)	0.00	0.00	0.46	0.00	0.00	0.22
Total electricity consumption	0.43	0.50	0.85	0.42	0.56	0.70
Total non-electricity energy consumption	0.37	0.46	0.81	0.25	0.36	0.47
Total CO2 Generation	0.41	0.50	0.86	0.25	0.36	0.47
CO2 Intensity of GDP (CO2/GDP)	0.37	0.38	0.40	0.22	0.25	0.23

Table 5. Summary results for the CO2 intensity of GDP for the energy efficiency improvement simulated in cases EA1-EA4

	Scotland			UK		
Labour market:	Real wage bargaining			Real wage bargaining		
	Short run	Long run		Short run	Long run	
		Migration on	Migration off		Migration on	Migration off
Key production parameters:						
Inelastic (0.8):						
All 25 sectors (EA1)						
CO2/GDP	0.94%	1.78%	1.81%	0.29%	-0.19%	-0.25%
CO2 level	Rise	Rise	Rise	Rise	Rise	Fall
20 non-energy supply sectors (EA3)						
CO2/GDP	-0.22%	-0.28%	-0.27%	-0.33%	-0.33%	-0.36%
CO2 level	Fall	Fall	Fall	Fall	Rise	Fall
Elastic (1.1):						
All 25 sectors (EA2)						
CO2/GDP	2.12%	2.77%	2.82%	1.70%	1.33%	1.29%
CO2 level	Rise	Rise	Rise	Rise	Rise	Rise
20 non-energy supply sectors (EA4)						
CO2/GDP	0.22%	0.47%	0.25%	0.37%	0.40%	0.38%
CO2 level	Rise	Rise	Rise	Rise	Rise	Rise

Table 6. Case LA1: Impacts (% Change from base year values) of a 5% increase in exogenous energy-augmenting technological progress applied to all 25 production sectors in the UK and Scottish economies - key KLEM production parameters (0.8)

	UK			Scotland		
	Short run	Long run		Short run	Long run	
		No migration	Migration		No migration	Migration
GDP (income measure)	3.67	6.04	15.45	3.46	5.70	8.27
Consumption	2.30	3.78	11.98	1.15	2.38	4.31
Investment	5.75	5.01	13.29	5.98	4.57	6.74
Exports	4.09	7.37	16.38	2.70	4.86	6.78
Imports	0.23	-1.50	-1.06	0.27	0.14	0.64
Nominal before-tax wage	-0.69	-1.03	-7.39	-0.59	-0.55	-2.57
Real T-H consumption wage	1.22	2.57	0.00	0.47	1.33	0.00
Consumer price index	-1.88	-3.51	-7.39	-1.05	-1.85	-2.57
Total employment (000's):	0.81	1.61	11.36	0.48	1.32	4.06
Unemployment rate (%)	-10.14	-20.10	0.00	-4.05	-11.05	0.00
Total population (000's)	0.00	0.00	11.36	0.00	0.00	4.06
Total electricity consumption	3.55	5.85	15.70	2.95	6.34	9.38
Total non-electricity energy consumption	3.43	5.83	15.86	2.08	4.60	6.95
Total CO2 Generation	3.49	6.00	16.12	2.11	4.77	7.17
CO2 Intensity of GDP (CO2/GDP)	-0.17	-0.04	0.58	-1.31	-0.88	-1.02

Table 7. Case LA2: Impacts (% Change from base year values) of a 5% increase in exogenous energy-augmenting technological progress applied to all 25 production sectors in the UK and Scottish economies - key KLEM production parameters (1.1)

	UK			Scotland		
	Short run	Long run		Short run	Long run	
		No migration	Migration		No migration	Migration
GDP (income measure)	3.95	5.83	15.91	3.82	5.62	8.80
Consumption	2.55	3.68	12.58	1.61	2.51	4.97
Investment	5.74	4.27	12.37	6.12	3.99	6.39
Exports	4.19	7.03	16.53	2.80	4.56	6.81
Imports	0.00	-1.71	-1.49	0.33	-0.01	0.55
Nominal before-tax wage	-0.19	-0.77	-7.44	-0.07	-0.21	-2.58
Real T-H consumption wage	1.86	2.68	0.00	1.03	1.56	0.00
Consumer price index	-2.01	-3.36	-7.44	-1.08	-1.74	-2.58
Total employment (000's):	1.20	1.67	12.52	1.03	1.52	5.06
Unemployment rate (%)	-15.06	-20.87	0.00	-8.64	-12.77	0.00
Total population (000's)	0.00	0.00	12.52	0.00	0.00	5.06
Total electricity consumption	3.69	5.36	15.54	3.15	5.81	9.34
Total non-electricity energy consumption	3.61	5.41	15.88	2.27	4.20	6.94
Total CO2 Generation	3.67	5.53	16.03	2.30	4.35	7.15
CO2 Intensity of GDP (CO2/GDP)	-0.26	-0.28	0.10	-1.46	-1.20	-1.52

Table 8. Case LA3: Impacts (% Change from base year values) of a 5% increase in exogenous energy-augmenting technological progress applied to the 20 energy use sectors in the UK and Scottish economies - key KLEM production parameters (0.8)

	UK			Scotland		
	Short run	Long run		Short run	Long run	
		No migration	Migration		No migration	Migration
GDP (income measure)	3.61	5.96	15.10	3.41	5.56	8.02
Consumption	2.22	3.70	11.67	1.11	2.29	4.12
Investment	5.67	4.94	12.98	5.85	4.44	6.49
Exports	4.12	7.31	16.07	2.62	4.70	6.52
Imports	0.24	-1.50	-1.06	0.22	0.06	0.55
Nominal before-tax wage	-0.70	-1.05	-7.24	-0.61	-0.59	-2.52
Real T-H consumption wage	1.15	2.50	0.00	0.44	1.27	0.00
Consumer price index	-1.83	-3.47	-7.24	-1.05	-1.84	-2.52
Total employment (000's):	0.77	1.57	11.04	0.46	1.26	3.87
Unemployment rate (%)	-9.60	-19.65	0.00	-3.83	-10.58	0.00
Total population (000's)	0.00	0.00	11.04	0.00	0.00	3.87
Total electricity consumption	3.43	5.74	15.30	2.42	5.36	8.21
Total non-electricity energy consumption	3.21	5.66	15.39	1.67	3.86	6.07
Total CO2 Generation	3.25	5.82	15.64	1.64	3.92	6.18
CO2 Intensity of GDP (CO2/GDP)	-0.35	-0.13	0.47	-1.71	-1.55	-1.70

Table 9. Case LA4: Impacts (% Change from base year values) of a 5% increase in exogenous energy-augmenting technological progress applied to the 20 energy use sectors in the UK and Scottish economies - key KLEM production parameters (1.1)

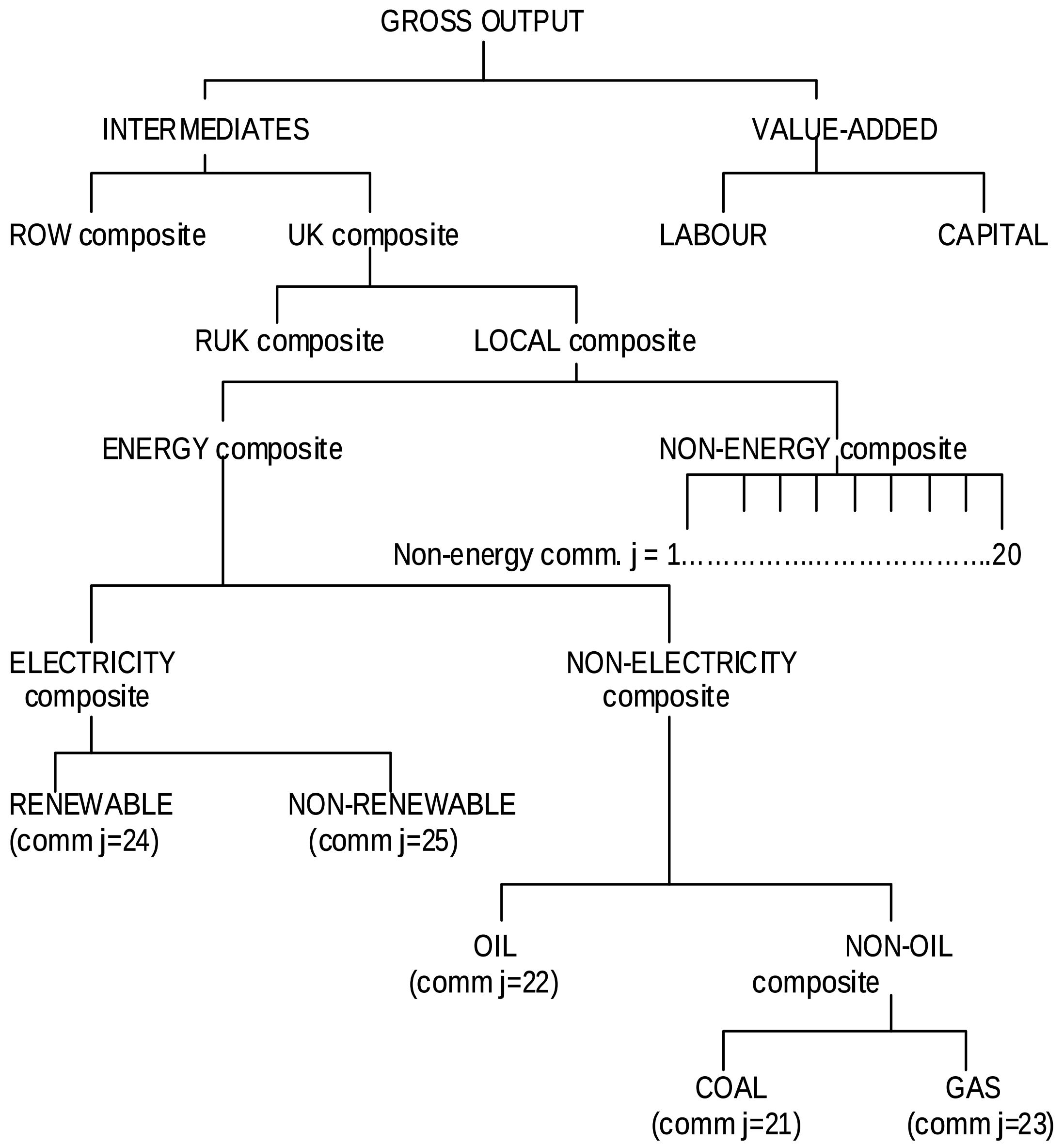
	UK			Scotland		
	Short run	Long run		Short run	Long run	
		No migration	Migration		No migration	Migration
GDP (income measure)	3.88	5.75	15.54	3.75	5.49	8.53
Consumption	2.46	3.60	12.24	1.55	2.42	4.77
Investment	5.69	4.21	12.09	5.97	3.86	6.17
Exports	4.21	6.98	16.21	2.71	4.41	6.56
Imports	0.01	-1.70	-1.49	0.26	-0.08	0.46
Nominal before-tax wage	-0.21	-0.78	-7.29	-0.11	-0.26	-2.53
Real T-H consumption wage	1.78	2.61	0.00	0.99	1.49	0.00
Consumer price index	-1.95	-3.31	-7.29	-1.09	-1.73	-2.53
Total employment (000's):	1.16	1.63	12.18	0.99	1.47	4.85
Unemployment rate (%)	-14.46	-20.41	0.00	-8.32	-12.30	0.00
Total population (000's)	0.00	0.00	12.18	0.00	0.00	4.85
Total electricity consumption	3.60	5.27	15.16	2.51	4.86	8.19
Total non-electricity energy consumption	3.42	5.26	15.43	1.78	3.48	6.07
Total CO2 Generation	3.45	5.37	15.56	1.74	3.54	6.17
CO2 Intensity of GDP (CO2/GDP)	-0.42	-0.36	0.02	-1.94	-1.85	-2.18

Table 10. Summary results for the CO2 intensity of GDP for the labour efficiency improvement simulated in cases EA1-EA4

		Scotland			UK		
		Real wage bargaining			Real wage bargaining		
Labour market:		Short run	Long run		Short run	Long run	
			Migration on	Migration off		Migration on	Migration off
Key production parameters:							
Inelastic (0.8):							
All 25 sectors							
	CO2/GDP	-1.31%	-1.02%	-0.88%	-0.17%	0.58%	-0.04%
	CO2 level	Rise	Rise	Rise	Rise	Rise	Rise
20 non-energy supply sectors							
	CO2/GDP	-1.71%	-1.70%	-1.55%	-0.35%	0.47%	-0.13%
	CO2 level	Rise	Rise	Rise	Rise	Rise	Rise
Elastic (1.1):							
All 25 sectors							
	CO2/GDP	-1.46%	-1.52%	-1.46%	-0.26%	0.10%	-0.28%
	CO2 level	Rise	Rise	Rise	Rise	Rise	Rise
20 non-energy supply sectors							
	CO2/GDP	-1.94%	-2.18%	-1.85%	-0.42%	0.02%	-0.36%
	CO2 level	Rise	Rise	Rise	Rise	Rise	Rise

Figures

Figure1. 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 Impact on UK consumpiton of UK supplied electricty and non-electricity energy due to a 5% energy efficiency improvment with migration flow on and off - key production elasticities 0.8

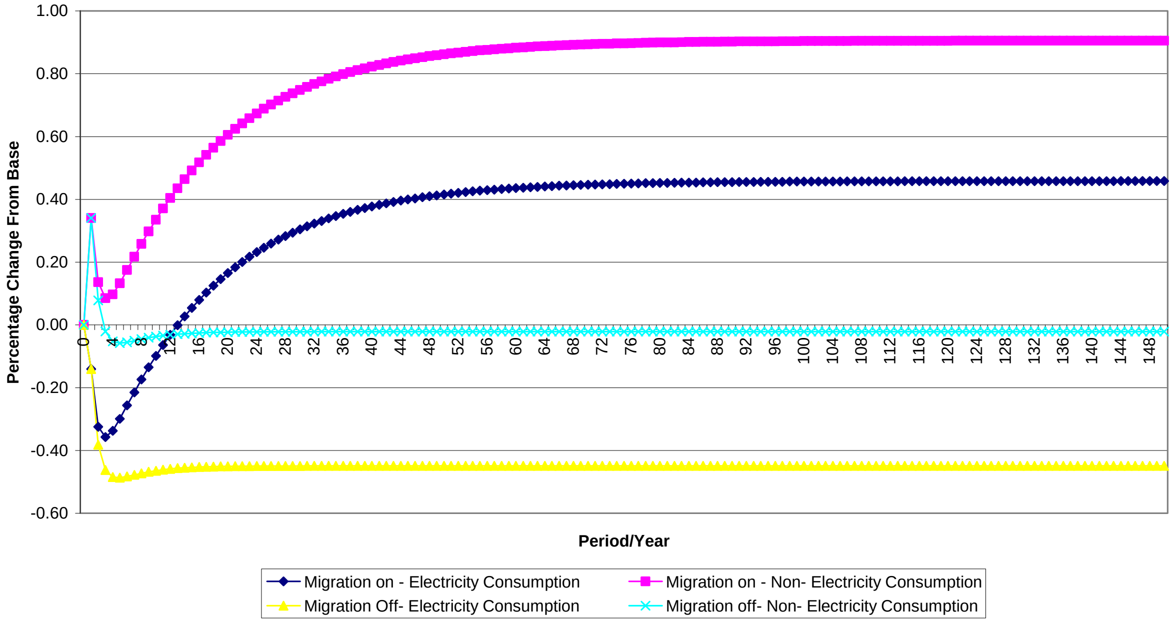


Figure 3 Impact on the level of CO2 emissions and GDP generated in the UK economy due to a 5% energy efficiency improvement applied to all 25 Sectors in the UK economy with migration flow on and off- key production parameters 0.8

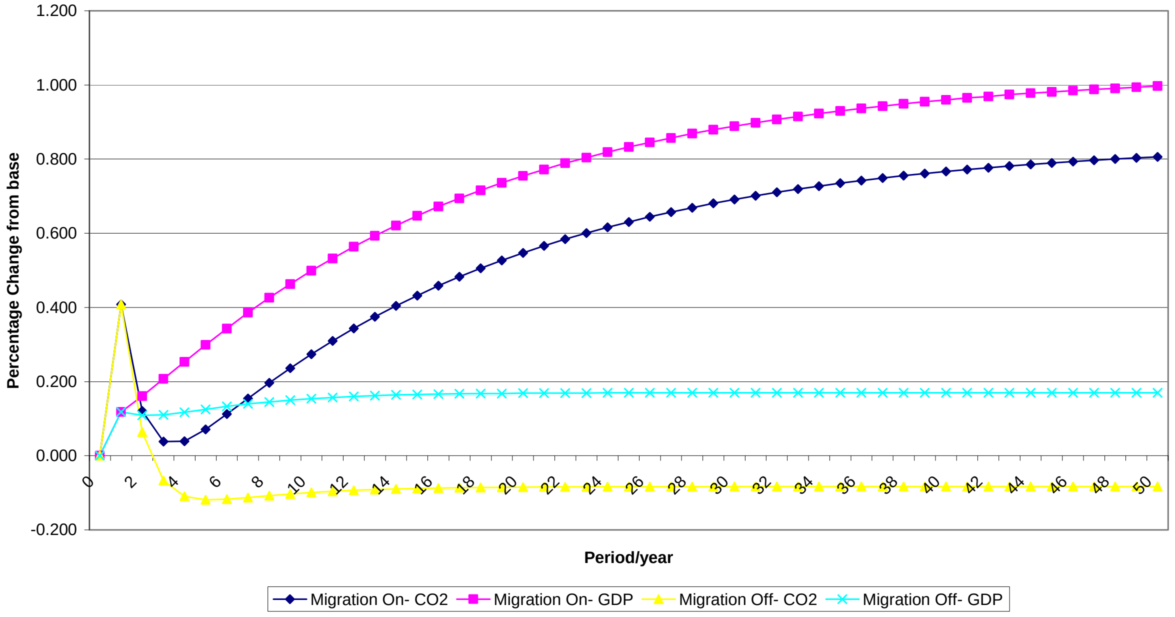


Figure 4- Impact on the Level of CO2 Emissions and GDP Generated in all 25 Sectors of the UK Economy due to a 5% Labour Efficiency Improvement with Migration Flow on and Off- Key Production Parameters 0.8