A comparison of results from MRIO and interregional computable general equilibrium (CGE) analyses of the impacts of a positive demand shock on the 'CO2 trade balance' between Scotland and the rest of the UK

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Abstract

In previous work we have applied the environmental multi-region input-output (MRIO) method proposed by Turner et al (2007) to examine the 'CO2 trade balance' between Scotland and the Rest of the UK. In McGregor et al (2008) we construct an interregional economy-environment input-output (IO) and social accounting matrix (SAM) framework that allows us to investigate methods of attributing responsibility for pollution generation in the UK at the regional level. This facilitates analysis of the nature and significance of environmental spillovers and the existence of an environmental 'trade balance' between regions. While the existence of significant data problems mean that the quantitative results of this study should be regarded as provisional, we argue that the use of such a framework allows us to begin to consider questions such as the extent to which a devolved authority like the Scottish Parliament can and should be responsible for contributing to national targets for reductions in emissions levels (e.g. the UK commitment to the Kyoto Protocol) when it is limited in the way it can control emissions, particularly with respect to changes in demand elsewhere in the UK.

However, while such analysis is useful in terms of accounting for pollution flows in the single time period that the accounts relate to, it is limited when the focus is on modelling the impacts of any marginal change in activity. This is because a conventional demand-driven IO model assumes an entirely passive supply-side in the economy (i.e. all supply is infinitely elastic) and is further restricted by the assumption of universal Leontief (fixed proportions) technology implied by the use of the A and multiplier matrices. In this paper we argue that where analysis of marginal changes in activity is required, a more flexible interregional computable general equilibrium approach that models behavioural relationships in a more realistic and theory-consistent manner, is more appropriate and informative.

To illustrate our analysis, we compare the results of introducing a positive demand stimulus in the UK economy using both IO and CGE interregional models of Scotland and the rest of the UK. In the case of the latter, we demonstrate how more theory consistent modelling of both demand and supply side behaviour at the regional and national levels affect model results, including the impact on the interregional CO2 'trade balance'.

Keywords: CGE modelling, MRIO, CO2 trade balance, environmental responsibility

1. Introduction

Input-output (IO) analysis is a powerful accounting tool for examining the structure of economic activity and associated issues such as the pollution and/or resource use engendered or embodied, directly or indirectly, in production, consumption and trade flows under different accounting principles (Munksgaard and Pedersen, 2001). Particularly in the ecological footprint literature, where focus is on accounting for emissions under the consumption accounting principle, IO analysis has become an increasingly commonly used technique to measure and allocate responsibility for emissions generation (see Wiedmann et al., 2007, for a review). As explained by Turner et al. (2007) this would seem a natural development, given that the focus of ecological or carbon footprints is to capture the *total* (direct plus indirect) resource use or emissions embodied in final consumption in an economy. IO analysis is based around a set of sectorally disaggregated economic accounts, where inputs to each industrial sector, and the subsequent uses of the output of those sectors, are separately identified. Therefore, by the use of straightforward mathematical routines, the interdependence of different activities can be quantified, and all direct, indirect and, where appropriate, induced, resource use embodied within consumption can be tracked (Leontief, 1970, Miller and Blair, 1985). Turner et al. (2007) go on to derive a multi-region IO method that is appropriate for accounting for emissions under the production and consumption accounting principles and determining environmental trade balances.

However, where concern lies in analysing the impacts of changes in policy, or other disturbances, on variables of interest, such as environmental trade balances, a more flexible framework is required. Such a framework should allow us to model both supply and demand side behaviour, and prices and quantities simultaneously and endogenously. An approach that incorporates the main strengths of IO for the treatment of environmental problems – i.e. the multi-sectoral, system wide features of IO tables – but that builds a more flexible analytical framework around this is computable general equilibrium (CGE) modelling. CGE modelling is now firmly established in the academic literature as the dominant approach for analysing global, national and regional environmental issues (see, for example, Bergman, 1988, Beausejour et al., 1995, Conrad, 1999, Welsch, 1996, Wissema and Dellink 2007). Environmental CGE modelling frameworks based on the AMOS framework developed by Harrigan et al (1991) have been developed for Scotland and the UK - see, respectively, Hanley et al (2006), and Allan et al (2007) - primarily (to date) to examine the system-wide impacts of improvements in energy efficiency. However, in order to analyse issues relating to environmental trade balances between the regions of the UK, and between the UK and the rest of the world, an interregional CGE modelling framework is required. While interregional CGE models are fairly commonly applied at the international level, commonly through the application of the GTAP framework (Hertel, 1997)[1], they are less developed at the sub-national level and have not, to our knowledge, been employed to extend the resource use/pollution accounting and environmental trade balance analysis that has become common in the IO literature.

Therefore, in this paper we employ a very simple 2-region, 3-sector variant of the UK AMOS framework (see Gilmartin et al. 2007a,b) to conduct some illustrative analysis and demonstrate the potential contribution of interregional CGE modelling techniques to environmental trade balance analysis. We compare the results of introducing a positive demand stimulus in the UK economy using both IO and CGE

[1] More information on application of the GTAP framework can be found at http://www.gtap.org.

interregional models of Scotland and the rest of the UK (RUK). In the case of the latter, we demonstrate how alternative specifications of a key element of supply-side behaviour at the regional and national levels, wage determination, effect model results, including the impact on the interregional CO2 'trade balance'.

The remainder of the paper is structured as follows. In Section 2 we calculate the base year (1999) CO2 trade balance between Scotland and RUK, then examine the impacts on key economic variables and the CO2 trade balance of introducing a 10% increase in export demand from the rest of the world to one of the production sectors in the Rest of the UK using the IO framework as a model. Then, in Section 3, we outline the AMOSRUK interregional CGE model, which shares the IO database but introduces an active supply-side and more theory-consistent specification of production and consumption behaviour (in particular, relaxing the assumption of universal Leontief technology). In Section 4, we introduce the same positive demand stimulus to the CGE model and compare the results with those from the IO reported in Section 2. A summary and conclusions of our analysis are provided in Section 5.

2. Input-output analysis of the CO2 trade balance between Scotland and RUK

2.1 The interregional IO framework

As in McGregor et al (2008) we apply the 2-region framework as derived by Turner *et al* (2007), where the standard interregional IO framework (Miller and Blair, 1985) is augmented with a 1x2N vector of output-pollution coefficients for a single pollutant, CO2, $\mathbf{e}_\mathbf{r}^\mathbf{x}$, with elements e_i^r telling us the physical amount of CO2 directly generated per unit of output, x_i, produced by sector i in region r:

[1] $$e_i^r = p_i^r / x_i^r$$

so that

[2] $$\begin{pmatrix} p_{11}^y & p_{12}^y \\ p_{21}^y & p_{22}^y \end{pmatrix} = \begin{pmatrix} \mathbf{e}_1^\mathbf{x} & \mathbf{0} \\ \mathbf{0} & \mathbf{e}_2^\mathbf{x} \end{pmatrix} \begin{pmatrix} \mathbf{I} - \mathbf{A}_{11} & -\mathbf{A}_{12} \\ -\mathbf{A}_{21} & \mathbf{I} - \mathbf{A}_{22} \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{y}_{11} & \mathbf{y}_{12} \\ \mathbf{y}_{21} & \mathbf{y}_{22} \end{pmatrix}$$

(where Scotland is region 1 and RUK is region 2, here with the IO framework aggregated to the 3 sectors we are able to model in the interregional CGE framework, so that each region has i=1,.., N=3 production sectors producing j=1,.., N=3 commodities). The first subscript on each element of [1] identifies the producing region, r, and the second the consuming region, s. p_{rs}^y is a scalar telling us the amount of CO2 generated in production activities in region r to support region s final demand, for output produced in region r, $\mathbf{y}_{\mathbf{rs}}$ (an Nx1 = 10x1 vector). $[\mathbf{I} - \mathbf{A}]^{-1}$ is the symmetric 2Nx2N (6x6) partitioned interregional Leontief inverse (multiplier) matrix, with elements b_{ij}^{rs} telling us the amount of output of each producing sector i in region r required per unit of final demand for the output of consuming sector j in region s.

Note that the description of a 2Nx2N (3x3) interregional Leontief inverse, where we have N=3 production sectors in each Scotland and RUK, is consistent with the conventional 'Type I' case where the A-matrix has elements a_{ij}^{rs} telling us the amount of output produced by each sector *i* in region *r*, x_{ij}^{rs}, required as input to production per unit of total input/output in consuming sector *j* in region *s*, X_j^s. Thus, each element of the A-matrix is formally defined as follows:

[3] $$a_{ij}^{rs} = x_{ij}^{rs} / X_j^s$$

In the conventional Type I case, the production sectors are those identified as production sectors in the IO accounts for the country in question. It is, however, possible to endogenise activities reported as final consumption sectors in the IO accounts – and, therefore, initially included in the partitioned matrix **Y** in the Type I case – by redefining the **A** and **Y** matrices.

Here, in order to make the IO analysis more consistent with a CGE analysis (where household income and expenditure is determined endogenously)[2], we carry out a Type II analysis, where household consumption is endogenised by subtracting household final consumption expenditure from each vector $\mathbf{y_{rs}}$, and adding an additional column and row of input-output coefficients to the **A**-matrix. In the additional row x_{ij}^{rs} will record use of region *r* household production (additional production sector, *i*) as inputs to production in sector *j* in region *s* and X_j^s will be the total input/output of sector *j* in region *s* (as above). In an IO account, household production is solely composed of the provision of labour services, so the additional row entries will be payments to labour services, or 'income from employment', divided by total input/output. In the case of households, where no labour is directly employed the coefficient will collapse to zero. In the additional column, x_{ij}^{rs} will record use of local inputs from each production sector, *i*, by the household sector, *j* (formerly recorded as final consumption) and X_j^s as the total input/output of households in region *s*, which is given by total payments to labour/income from employment.

If final consumers also directly generate emissions of CO2, in the Turner et al (2007) method these are determined using a 1x*Z* vector, $\mathbf{e_r^y}$, of coefficients giving the amount final expenditure-pollution coefficients for each final consumption group *z* in each region *r*, with each element e_z^r telling us the physical amount of CO2 directly generated per unit of final expenditure, f_z. In the current study only one final consumption group, households (hh), is responsible for direct emissions generation, and, in our Type II analysis households move into the production block as a fourth sector in each region. Therefore, direct emissions generation by households is accounted for by extending the $\mathbf{e_r^x}$ vector in each region with the additional elements e_i^r, where *i* represents the household sector producing labour services, and we have the physical amount of CO2 directly generated per unit of income from employment (the valuation of household labour services).

[2] There will not be a one-to-one correspondence between the IO and CGE analyses in this regard as the CGE framework includes non-wage household income. Note also that since household expenditure does not tend to balance with household income in an IO framework (since not all elements of income and expenditure are included), strictly speaking we should retain a portion of household expenditure as being exogenously determined, or use a social accounting matrix (SAM) in place of the IO accounts.

The 2x2 partitioned **P** matrix derived in [2] for the Type II case gives us total emissions in regions 1 and 2 attributed to final consumption demand in each region for the outputs of the 2 regions. The total emissions generated in region 1 (Scotland), p_1, are given by summing along the first row of each **P** matrix so that

[4] $$p_1 = p^y_{11} + p^y_{12}$$

while the total emissions in both regions of the UK that are supported by region 1 (Scottish) final consumption demand are given by summing down the first column of each **P** matrix so that

[5] $$p^y_1 = p^y_{11} + p^y_{21}$$

The corresponding calculations for RUK are carried out using the second row and column of the **P** matrix.

According to Munksgaard and Pedersen's (2001) method, Scotland's CO2 trade balance with RUK would be calculated as the difference between [4] and [5]. However, the distinction here is that the UK is not a closed economy, with the implication that [5] does not fully account for Scottish emissions under Munksgaard and Pedersen's (2001) consumption accounting principle. This would require extending the interregional system in [2] to include other trading region(s), which would, among other things, require information on the commodity breakdown of imports and corresponding pollution technologies. The data to do this for the UK are not currently available. Other authors (e.g. Druckman et al, 2007) have attempted to extend IO attribution analyses under the consumption accounting principle using, for example, the assumption that domestic production and pollution technology applies to imports. In McGregor et al (2008) we address this issue by fully endogenising trade in what we refer to as a Trade Endogenised Linear Attribution System (TELAS), closing the system at the national level under the production accounting principle. Here, for simplicity (given the illustrative nature of our current analysis) we do not attempt any such treatment, instead allowing domestic emissions to be attributed to demand from the rest of the world (ROW), with the implication that emissions attributable to ROW demand for Scottish output will be allocated to Scotland's pollution account, and similarly for ROW demand for RUK outputs. However, appropriate extensions of the framework will be addressed in future research.

2.2 Type II Scotland-RUK environmental trade balance results

A number of data problems were encountered in constructing the interregional IO and SAM framework used in this paper. These are explained in McGregor et al (2008). However, the questions over the reliability of the data mean that the quantitative results of any analyses using the Scotland-RUK environmental IO and CGE models should be regarded as provisional. Nonetheless, we believe that there is still merit in using the framework for an illustrative attribution analysis to examine the nature and level of interdependence between regions of the UK, specifically in terms of environmental spillover effects, the existence of a CO2 'trade balance', and the impacts on key variables when a demand disturbance is introduced to the system.

Table 1 shows the results of estimating equation [2] for the Type II case (i.e. with household expenditure endogenised within the interregional A-matrix), with all

CO2 emissions generated in the UK allocated to the remaining final demand categories in each region.

Table 1 shows the scale of the CO2 "trade" (or "spillovers") that occur between Scotland and the rest of the UK. Of the total CO2 generated in the UK directly or indirectly as a result of conventional Scottish final demand expenditures, just over 45% is generated in RUK (i.e. not in Scotland). A smaller, but still significant, proportion (just over 38%) of CO2 generated in Scotland is to support, directly or indirectly, RUK final demand. Also note that Scottish exports to the rest of the world, which produce no direct CO2 outwith Scotland, still generate sizeable amounts of CO2 in the RUK as a result of the indirect impacts of the production of intermediate inputs, and similarly for the impact of RUK exports to the ROW in terms of CO2 emissions in Scotland.

There is a negative CO2 trade balance for Scotland, implying that the pollution generated in Scotland by production to support RUK final demands is less than the pollution generated in the RUK by production supporting Scottish final demands. This Type II Scottish CO2 trade deficit equates to around 13% of total CO2 generated in Scotland. Note, however, that the precise levels and proportions of emissions attributable to different activities, and the size of the CO2 trade balance in Table 1 are dependent on the Type II assumption employed here. See McGregor et al (2008) for the impacts of adopting different assumptions (Type I and TELAS) in the same framework For example, when trade is endogenised, under the TELAS assumption, Scotland's CO2 trade deficit becomes a surplus, due to Scotland being a net exporter to the ROW, while the RUK region is a net importer.

In the current paper our interest lies in the use of interregional general equilibrium frameworks for analysing the impact of any marginal *change* in activity. It is our argument that the interregional IO framework is limited in this regard. First, the system in [2] is a conventional demand-driven IO model which is silent on prices and assumes an entirely passive supply-side in the economy (i.e. all supply is infinitely elastic in response to changes in final demand, within the **Y** matrix). Moreover, it is further restricted by the assumption of universal Leontief (fixed proportions) technology implied by the use of the **A** and Leontief multiplier matrices. It is possible to construct a supply-driven IO model (Oosterhaven, 1988, 1989) or a price dual to the demand model (Leontief, 1970, Allan et al, 2007). However, in either case, the assumption of universal Leontief technology still applies and it is only possible to model supply *or* demand, or prices *or* quantities. Our argument is that where analysis of marginal changes in activity is required, a more flexible interregional CGE approach, which models behavioural relationships in a more realistic and theory-consistent manner, is more appropriate and informative. This will be demonstrated by comparing the results of introducing the same positive demand stimulus to the UK economy using our IO and CGE interregional models of Scotland and the RUK. Note that in the CGE framework it would be possible to model the impacts of a supply-side shock also. However, in order to compare 'like with like', in the current paper we focus on a demand disturbance, but use the CGE model to demonstrate how alternative specification of supply-side behaviour at the regional and national levels effect model results.

The disturbance we will model is a 10% increase in export demand from the ROW to the RUK Primary, Manufacturing and Construction sector. This is not intended to be a representation of a realistic, or likely, demand shock. Rather, our intention in this very aggregated framework is to illustrate the importance of interregional trade linkages in modelling the impacts of marginal changes.

The shock is introduced to the model by changing the value of the y_2^{ROW} vector in the matrix of final demand in equation [2] to represent a 10% increase in ROW export demand to sector 1 in region 2, RUK (Table 2 shows the sectoral breakdown of production in each region). Table 3 shows the impacts of the disturbance (in terms of percentages changes given by the base of the 1999 IO tables) on sectoral output (income from employment in the case of households), value-added (equating to GDP at basic/producer prices), employment and direct CO2 emissions.

There are two key points to note. First, note that at the sectoral level the percentage change in each variable is the same. This is due to the assumption of Leontief technology (if output changes by X%, use of all inputs changes by X%). Second, there is no indication as to the time taken to reach the new post-shock equilibrium. We will return to both these issues in Section 4, where the CGE results of the same shock are discussed.

The post-shock CO2 attribution and trade balance analysis is shown in Table 4. This is comparable with Table 1 above, and the difference between the two tables is shown in percentage terms in Table 5. In terms of the impact of the shock, the key result to note is that Scotland's CO2 trade balance improves in response to this shock. The deficit in Table 4 is reduced relative to the base case shown in Table 1. Table 5 shows that the driver of this is the fact that the amount of pollution generated in Scotland to support RUK final demand has risen by 6.72%. This leads to an 8.41% reduction in the size of Scotland's CO2 trade deficit with the RUK. Almost half (46%) of this change in the CO2 trade balance is due to the increase in emissions from the Scottish Electricity, Gas and Water Supply sector. This sector in Scotland is heavily trade-reliant, exporting almost 26% of its output to RUK in the base year of 1999 (in contrast to the RUK Electricity, Gas and Water Supply sector, which exported less than 1% of its output to Scotland in 1999).

However, in methodological terms, note that the increase in Scottish and RUK UK emissions to support RUK final demand is the only change in Tables 4 and 5. This reflects the fact that there is no response in any other type of final demand, and this would not be expected given that (a) all other final demands are determined exogenously; (b) even if other final demands were determined endogenously, there is no change in prices to stimulate further changes. As we will see next, in a CGE analysis neither of these assumptions is required.

3. AMOSUK: an interregional CGE model of the UK economy (Scotland-RUK)

AMOSRUK, the interregional version of the AMOS simulation framework[3], is a computable general equilibrium model of the UK economy with two endogenous regions, Scotland and the RUK and one exogenous region, the ROW. Our CGE modelling approach allows for a more comprehensive analysis of the effects of the demand disturbance than the preceding IO analysis for a number of reasons. Firstly, the model structure enables us to overcome some of the technical limitations presented by our IO model, in particular the restrictions associated with an entirely passive supply side in the economy and the assumption of universal Leontief technology. Secondly, the versatility of the CGE modelling framework means that we can consider a range of model closures corresponding to different time periods of analysis and labour market

[3] Harrigan et al (1991) gives a full description of early versions of the AMOS framework, and Gillespie et al (2002) describes the interregional model AMOSRUK. Greenaway et al (1993) provides a general appraisal of CGE models and Partridge and Rickman (1998, 2008) review regional CGEs.

options, and their impact on the adjustment of the economy following the initial demand disturbance.

The core database for the CGE model is an interregional Social Accounting Matrix (SAM) for 1999, which provides a 'snapshot' of the Scottish and rest of the UK economies for that year. The SAM is basically an augmented IO table that incorporates information on income transfer payments between aggregate economic agents and factors of production.[4] It covers all intra-regional, interregional and international transactions in the economy that year, highlighting the linkages that exist between production sectors and final consumers in the two regions. The structural data embedded in the SAM are used to ascribe actual values to some of the model's parameters (for example the relative size and import intensity of sectors). Other parameter values are determined exogenously (for example parameters in the migration and wage setting functions and price elasticities of demand and substitution). These are informed by a combination of econometric estimation, literature review and the modeller's judgement, and can all be subjected to sensitivity analysis. A final set of parameter values is determined through calibration of the model to reproduce the base year dataset. Where econometrically parameterised relationships have been imposed, these have been determined using annual data, as has the SAM, with the implication that each 'period' in the model can be interpreted as a single year.

In AMOSRUK, we treat each endogenous region in a similar manner to that adopted in our single-region Scottish model, AMOS (Harrigan et al, 1991). In the interregional variant, however, the individual regions are linked by trade and potential migration flows, generally determined by endogenous changes in prices, wages and activity in both regions.[5] The model structure incorporates three transactor groups in each region – households, firms and the government – and three commodities and activities – 'Primary, Manufacturing and Construction', 'Electricity, Gas and Water Supply', and 'Services' (Table 2).[6] There are four main components of final demand: household consumption, investment, government expenditure and exports to the ROW. In production, local intermediate inputs are combined with imports from the other region and the rest of the world via an Armington link (Armington, 1969). This means that domestic products and imported goods are treated as imperfect substitutes, with the degree of substitutability determined by the modeller at the parameter specification stage (as explained above), and, thus, subject to sensitivity analysis. The composite intermediate input is then combined with labour and capital (value added) to determine each sector's gross output. Production functions at each level of the production hierarchy can be CES, Cobb-Douglas or Leontief. The simulations in this paper use CES production functions at the value-added and gross-output level, and Leontief productions functions at the intermediate-inputs level in each region.[7] Thus, unlike in our IO framework, we allow for substitution between factor inputs – for example in response to changes in the relative price of labour and capital – at the value-added and gross output level, as well as between Scottish and RUK goods, and the UK composite and imports from ROW. As noted above, both interregional and international exports

[4] Details on the SAM used here can be found in McGregor et al (2008).
[5] In the single-region version Scottish prices, wages and activity are endogenous, but prices, wages and activity in the rest of the UK are exogenous.
[6] CGE models generally incorporate a greater degree of sectoral detail. This will be the focus of future research with AMOSRUK. At this stage the simple 3-sector, 2-region model is sufficient for the illustrative analysis we present here.
[7] In the current paper we have assumed Leontief production functions at the intermediate-inputs level to simplify the process of recreating IO tables off-line. In future developments this process will be an automatic output of the model and the Leontief assumption can be relaxed.

are price sensitive. However, while non-price determinants of export demand from the rest of the world are taken to be exogenous, export demand to the other UK region is fully endogenous, depending not only on relative prices, but also on the structure of all elements of intermediate and final demand in the other region.

A significant feature of the model, and a further advantage of this modelling framework relative to our IO model, is the endogeneity of capital and labour. For the capital stock, gross investment is determined by a capital-stock adjustment mechanism: in each period investment demand from each sector is a proportion of the difference between actual and desired capital stock, where desired capital stock is a function of commodity output, the nominal wage and the user cost of capital.[8] Thus in response to a shock, investment optimally adjusts capital stocks, gradually relaxing any capacity constraints. We also allow for the labour force to be updated following a shock. In the current application we assume that there is no natural population increase and no international migration, but in one of the simulations reported below the regional labour forces can be adjusted through interregional migration.

In the simulations reported here, we consider the period-by-period adjustment process of the economy following the shock, towards a new long-run equilibrium.[9] This approach provides a significant advantage over IO methods. Firstly, the period-by-period results provide a better appreciation of the adjustment path of the economy, the mechanisms at work to restore equilibrium, and the relative size and timings of the adjustments in each region. Secondly, at present, policy makers consider a ten-year time horizon for the evaluation of regional policies (HM Treasury, 1995), and so consideration of the adjustment path of the regional economies, rather than only long-run equilibrium results, provides important insights from a policy perspective. This is particularly noteworthy given that, as shown below, it may take significantly longer than 10 years to reach a new long-run equilibrium.

In addition, we consider the national constraints within which the system of regional economies operates, here assuming a national population constraint and its implications for regional wage determination. We simulate the demand disturbance to the RUK Primary, Manufacturing and Construction sector under different wage-setting and migration assumptions, each of which reflects a commonly-encountered view of how regional labour markets operate in the regional macroeconomic and labour market literature (see Appendix 1). The national economy is of course subject to certain other macroeconomic constraints. However, our treatment of these is straightforward. We assume that interest rates are exogenous and that the government operates a fixed exchange rate regime. The AMOSRUK model also provides the opportunity to impose constraints on the regional balance of payments and on public sector net transfers to the regions, though we do not make use of these options in the current analysis. Further, the framework allows for government expenditure to be endogenised in the regions. For the sake of tractability of model results, neither do we make use of this option in the study.

For the simulations reported here, the main default parameter values are set as follows: the elasticity of substitution in the CES production functions is set at 0.3

[8] The speed of adjustment of the capital stock – i.e. the proportion of gap between actual and desired capital stock filled between any two periods is an exogenously specified parameter.

[9] We take a long-run equilibrium to be one where capital and labour stocks have fully adjusted, which, in the demand shock examined here, allows all prices to return to their initial (pre-shock) levels. In this respect, we would consider the long run CGE equilibrium to be comparable to the post-shock IO equilibrium in the previous section (McGregor et al, 1996). However, we can also use the CGE framework to simulate supply-side shocks and constraints, which will not result in a long-run equilibrium that is comparable with IO.

(Harris, 1989) and the Armington assumption is applied to both interregional and international trade with an elasticity of substitution of 2.0 (Gibson, 1990). The parameter determining the speed of adjustment from actual to desired capital stock is set at 0.5, following econometric work on the determination of investment in the Scottish economy. These parameter estimates have been informed by a review of the relevant literature. It is important, however, that such model specifications be subject to rigorous and systematic sensitivity analysis. This is outwith the scope of the current paper, which is intended as an illustrative analysis, but will be reported in future papers.

4. CGE analysis of the CO2 trade balance between Scotland and RUK

4.1 Simulation strategy

The analysis reported in this section replicates the demand disturbance introduced to the interregional IO framework in Section 2.2. It considers the system-wide effects on Scotland and the RUK of a positive demand shock to the RUK Primary, Manufacturing and Construction sector. This involves a 10% step increase in ROW exports in this sector in the RUK in period 1, for each of three model configurations involving different views of wage determination in each region. We refer to these as:

1. Quasi IO - fixed real wages with population fixed at the regional level;
2. Bargaining - real wages are determined via a conventional 'wage curve' operating at the level of the region, with wages inversely related to the unemployment rate, and with population fixed at the regional level;
3. Flow Migration - regional wage bargaining as in (2) but with population fixed only at the national level. Interregional migration is determined by relative real wage and unemployment rates in Scotland and RUK.

See Table 6 and Appendix 1 for more details of the labour market configurations. Under each scenario the model is run forward for 75 periods with the values of all other exogenous variables held constant, and the changes from the initial base-period value are reported for the key variables. Crucially, though, all export demands are determined endogenously and respond to the relative price changes that occur in response to the initial exogenous demand shock. In all cases, investment is endogenous and sectoral capital stocks are updated between periods. Under the Flow Migration configuration the regional populations are adjusted in a similar manner. In the other scenarios, the regional populations remain constant.

The model calibration process takes the economy to be initially in long-run equilibrium, so that if the model is run forward with unchanged exogenous variables and parameters, the endogenous variables continuously take their initial values. Introducing a step change drives the economy towards a new long-run equilibrium and it is the paths to the new, comparative static, equilibria that are reported here. The different model configurations generate both different long run equilibria and different adjustment paths.

The simulation results are discussed for each model configuration in turn. Figures 1-14 show the trajectories for the change in key variables relative to base for the five model configurations. Figures 1-7 relate to the RUK economy; Figures 8-14 to the

Scottish economy. Each variable is expressed in terms of its change (absolute or percentage) relative to base.

4.2 Simulation results – key economic indicators

4.2.1. RUK Economy: Quasi IO Results

Figure 1 illustrates the simulated impact of the demand shock on RUK GDP under each of the labour market configurations, with the RUK being the region directly impacted by the demand shock. In all cases, the export stimulus leads to an increase in GDP relative to base towards a new, stable equilibrium. The increase is greatest for the Quasi IO configuration, with RUK GDP 2.8% above its base value by period 75 (which is slightly greater than the increase in total RUK value-added (2.63%) in the IO case). The economy is converging on a long-run equilibrium by period 75, though is has still not quite settled even after this amount of time, given the size of the demand shock.

As in the IO model, the demand shock leads to an increase in output in the RUK Primary, Construction and Manufacturing sector, and also in the wider economy, via an increase in the demand for intermediate inputs. However, in early periods supply constraints arise due to short-run capital fixity and the time taken for capital stocks to adjust. As commodity outputs increase due to the demand stimulus, prices rise in the short-run. There is upward pressure on the price of commodity outputs, value added and capital rental rates in the Primary, Manufacturing and Construction sector, and also on the overall CPI (see Figure 2). Prices rise in the other two RUK sectors, Electricity, Gas and Water Supply sector and the Services sector, due to the general increase in consumption demand, and also because intermediate inputs from these sectors are required in the Primary, Manufacturing and Construction sector production process. The effects are most significant in the Electricity, Gas and Water Supply sector, reflecting the importance of energy as an input to the manufacturing production process, though the effects are still less strong than in the Primary, Manufacturing and Construction sector itself. Prices in this sector are 1.5% higher than base values by period 3, compared with relative increases of 0.25% and 0.11% in the Electricity, Gas and Water Supply and Services sectors respectively.

With fixed real wages in this scenario, as output expands, nominal wages rise (Figure 3), but only in response to the increase in the CPI in the shorter run (Figure 2). This does result in a negative competitiveness effect in the short run, though this is reversed over time, and there is no adverse competitiveness effects generated specifically through the labour market in this scenario as export demand expands. However, note that due to the increase in prices when supply is constrained, there is a loss in competitiveness with the implication that the initial 10% increase in ROW export demand to Primary, Manufacturing and Construction is not realised from the outset (indeed by period 75, only a 9.94% increase is achieved). However, as prices and nominal wages converge towards their long-run equilibrium values in the Quasi IO scenario, this labour market configuration results in the highest increase in ROW exports over base, and this external export boost contributes to the strongest GDP trajectory for this configuration relative to the other scenarios. In line with the increase in GDP, the export shock increases the derived demand for labour across all sectors. The long-run employment effects are strongest in this scenario out of all the labour market configurations (Figure 4), with total employment 2.69% above base by the end of the simulation period.

4.2.2 Scottish Economy: Quasi IO Results

In this scenario, the RUK export shock also leads to a rise in long-run GDP in Scotland. As in the RUK economy, the Quasi IO results in Scotland are significantly stronger than for the other labour market configurations (Figure 8). The size of the impact as a percentage of GDP is, as expected, less significant for Scotland relative to the RUK, owing to the direct effect of the shock on the RUK economy.

In the Scottish economy, the stimulus results from an increase in the demand for Scottish intermediate goods by RUK producers, and also, in the longer run as activity expands in the RUK, for final consumption and investment goods. As in the RUK economy, real wages remain fixed in Scotland so that, as output expands, the Scottish economy does not experience negative competitiveness effects generated directly through the labour market. However, nominal wages increase in response to rising commodity outputs and the associated increase in CPI in the short-run, bringing about a significant negative external competitiveness effect: exports to the ROW fall by 1.85% in period 3, and this contributes to the short-run fall in overall GDP relative to base (Figure 8). Over time, as capacity constraints relax and prices move back toward their base year values, the negative competitiveness effect is removed (Figure 10), and the boost to RUK trade is sufficient to outweigh the negative external competitiveness effect in the long run (Figure 8).

As with the RUK economy, the increase in GDP is strongest for this scenario relative to the other model set-ups. The boost from interregional trade is strongest for the Quasi IO scenario, due to the absence of a long-run negative competitiveness effect in the RUK economy and the associated strongest increase in RUK GDP for this scenario. Furthermore, the impact of the negative competitiveness effects associated with rising wages are least strong in this scenario in Scotland relative to the Bargaining and Flow Migration case, due to real wages remaining fixed.

Although the overall impact of the RUK export shock is an increase in long run GDP in both regions, the effects of the stimulus are much slower to materialise in the Scottish economy compared with the RUK. In period 10, the relative increase in RUK GDP is 42.9% of its long run value. In contrast, Scottish GDP in period 10 is just over 6.22% of its period 75 value. This is attributable to the interregional transmission mechanism between the two economies and, in particular, the effects of the presence of supply-side constraints. The RUK economy receives an initial demand injection from an increase in ROW manufacturing exports, but supply constraints limit the impact in the short and medium run. The direct impact of the ROW demand stimulus is sufficient to dominate the adverse supply reaction in the RUK, however, leading to an overall increase in GDP, even in the short run (Figure 1)[10]. Over time, as capacity constraints relax, the full effects of the demand shock are transmitted to the wider RUK economy. The Scottish economy, in contrast, does not receive the immediate ROW demand stimulus. Rather, the demand boost for the Scottish economy is generated indirectly from an increase in the demand for intermediate and final goods from the RUK, and these effects take time to feed through. The differing source of the shock results in a very different adjustment process compared with that of the RUK. In fact there are significant adverse price implications for the Scottish economy in the short and medium run, which contribute to a fall in Scottish GDP relative to base until period 8. As UK activity rises following the shock and the price of UK intermediate goods increases, this

[10] This is true for the RUK economy across each of the labour market scenarios.

feeds through to higher prices in the Scottish economy (Figure 9), and an associated negative impact on external competitiveness and ROW exports in Scotland (Figure 14). Although there is a limited demand stimulus in Scotland via the expansion in RUK output and the increase in Scottish exports to the RUK (Figure 13), this is insufficient to outweigh the negative impact of the price effects. This holds true for all the labour market scenarios in Scotland in the short run (Figure 8). As capacity constraints optimally adjust in the UK over time, the full effects of the demand boost are transmitted to Scotland via interregional trade linkages, and this results in a protracted adjustment period for the Scotland economy (Figure 8).

The nature of the demand shock therefore has much more complex implications for the non-target region than straightforward IO analysis would imply. Whereas under IO analysis an increase in ROW exports for the RUK constitutes a pure demand shock, the active supply side response embodied in CGE analysis means that other-region effects are both demand and supply orientated, and this suggests that IO analysis would provide a very poor approximation of the effects of the shock in the presence of a non-passive supply side. Furthermore, the ability to analyse the period-by-period results reveals important insights about the adjustment process of the regional economies that are not uncovered by IO analysis: in particular, while the long run equilibrium outcome is a boost to GDP in Scotland, GDP is lower than base in the year following the shock, and for much of the Treasury's ten year time horizon for the evaluation of regional development policies.

4.2.3. RUK Economy: Bargaining Results

The results from the Quasi IO configuration serve as a useful benchmark against which the Bargaining and Flow Migration results can be compared. The introduction of bargained real wages, either without migration (the Bargaining scenario), or with migration (the Flow Migration scenario), reduces the size of the relative GDP stimulus in both the RUK and Scottish economies, as the responsiveness of wage rates gives rise to negative competitiveness effects that are maintained into the long run (Figures 1 and 8).

In the case of the Bargaining scenario, the relative increase in RUK GDP is the lowest out of all the configurations, with the long-run change in GDP around 25% of the value of the GDP stimulus in the Quasi IO scenario (Figure 1). In this set-up, as in the previous scenario, the export stimulus increases the derived demand for labour (Figure 4). With no interregional migration, real wages rise according to Equation A1 (Appendix 1), reflecting the tightness of the regional labour market (Figure 5). Commodity output prices therefore rise relative to base, as does the overall CPI (Figure 2). This represents a significant negative competitiveness effect: real wages are 0.82% higher than base by period 75 (compared with no change in the Quasi IO case) and economy-wide prices are 1.2% higher (compared with 0.03% in the previous scenario). Furthermore, while the negative competitiveness effect that occurred in the Quasi IO case was a short-run and indirect effect, in the bargaining set-up the effect remains significant for the duration of the simulation period, and operates directly through the labour market.

As a result of the reduction in RUK competitiveness relative to that in the Quasi IO case, the increase in RUK exports to the ROW is lower (ROW exports increase by 3.85% relative to base by period 75 in the Bargaining scenario, compared with 6.43% under the Quasi IO case). This is reflected in the weaker GDP stimulus under this market set-up, and accounts for a more subdued increase in total RUK employment relative to base over the period (Figure 4)[11].

4.2.4. Scottish Economy: Bargaining Results

The presence of bargained real wages similarly reduces the GDP stimulus in the Scottish economy compared to the effects under the Quasi IO scenario. Over time, as output expands and the derived demand for labour increases in Scotland, real wages are bid up (Figure 12). This reduces Scottish competitiveness relative to the Quasi IO case, leading to a larger fall in ROW exports (Figure 14) and increasing import penetration. Furthermore, the reduced GDP stimulus in the RUK economy – similarly associated with reduced RUK competitiveness as a result of the responsiveness of RUK wages – means that the increase in intermediate and final demands for Scottish exports is also relatively weaker under this scenario compared with the Quasi IO case. These effects together contribute to a significantly lower GDP stimulus in this case relative to the Quasi IO scenario. By period 75, GDP is 0.08% higher relative to base in this scenario, compared with 0.98% in the Quasi IO case.

4.2.5 RUK Economy: Flow Migration Results

The demand shock also results in a relative increase in Scottish GDP when migration is introduced (together with bargained real wages) compared with the Quasi IO case. In the Flow Migration case, the source of the long-run boost remains the same as in the previous two scenarios: higher export demand increases traded sector outputs, and the boost in activity feeds through to the wider economy.

In this model set-up, the responsiveness of the real wage works to reduce external competitiveness as activity rises, as in the Bargaining scenario. The introduction of migration, however, lessens this adverse effect to some extent. Immediately following the demand shock, the prices of value-added and commodity outputs rise in the traded sectors, and economy-wide prices increase relative to base (Figure 2). As in the Bargaining scenario, the resultant increase in output and the reduction in unemployment mean that real wages are bid up (Figure 5).

Here, as in the Bargaining scenario, the increase in real wages and consumer prices brings about a negative competitiveness effect, offsetting to some extent the demand shock (albeit that the overall increase in economic activity remains positive, with the negative supply-side effect from the wage increase being small relative to the demand injection). However the allowance for migration means that, following the shock in the RUK economy, some of the labour supply migrates away from Scotland and into the RUK economy, where the unemployment rate is relatively lower and real wages relatively higher than in the base period. Although there remains a UK-wide labour market constraint (zero net migration is assumed in the UK overall), there is some easing of labour market constraints in the RUK, but at the expense of a contraction in the Scottish labour supply. Thus the presence of interregional migration, and the increase in the labour supply in the RUK, works to mitigate the increase in RUK real wages in the long run (Figure 5) compared with the Bargaining scenario. However, the effects are muted: by period 75, real wages are 0.76% above their base values in the

[11] These results are in line with McGregor et al (1999), which considers the spillover effects and interdependencies between the Scottish and RUK economies in a CGE context. The authors examine a demand shock in the presence of local wage bargaining and no migration, and find that there is some crowding out of the employment injection through reduced competitiveness.

Flow Migration scenario, compared with 0.82% in the Bargaining case. The increase in nominal wages is therefore less in the Flow Migration case in the long run: nominal wages are 1.94% higher than base in period 75, compared with 2.03% in the Bargaining case. The presence of migration therefore reduces the loss in price competitiveness of RUK exports. RUK exports to the ROW are 3.95% higher, compared with 3.80% for the Bargaining scenario. As a result, the long-run GDP increase under the Flow Migration scenario is greater than under the Bargaining scenario, but still lower than under the Quasi IO case, where the real wage increase is zero, the price increases more subdued in the short run (and zero in the long run) and the negative competitiveness effect least prevalent (Figure 1).

4.2.6 Scottish Economy: Flow Migration Results

In contrast to the effects on the RUK economy, the introduction of interregional migration makes for an overall reduction in long-run GDP relative to base for Scotland (Figure 8). By the end of the simulation period, Scottish GDP is 0.86% below its base value. This compares with a relative increase in GDP of 0.98% for the Quasi IO scenario and 0.08% for the Bargaining closure.

As in the Bargaining scenario, the Scottish economy experiences an increase in export demand from the RUK economy (Figure 13). But the presence of migration works to counteract the Scottish stimulus in the Flow Migration scenario. Owing to the direct effects of the demand shock in the RUK, the increase in the real wage over time and the proportionate rise in employment relative to base are stronger in Scotland compared with the RUK. These changes in the Scottish/RUK unemployment and real wage ratios mean that some of the population flows into the RUK economy, and the Scottish economy experiences an adverse supply shock in the form of a reduced labour supply. In period 75, the Scottish population is 2.58% lower relative to base.[12]

The increase in demand for Scottish goods from the RUK economy, combined with reduced population, means that there is still upward pressure on commodity output prices and overall CPI in the Scottish economy (Figure 9). As in the RUK economy, this causes a detrimental effect on Scottish exports to the ROW (Figure 14). In contrast to that of the RUK, however, the overall effect of the demand disturbance in this scenario is a long run fall in GDP and employment relative to base (Figures 8 and 11). The source of the different outcomes is the effect on the regions' labour supply. When both regions have bargained real wages – without migration – each region experiences an increase in output and employment in the long run. This is because the reduced ROW competitiveness – brought about by the responsiveness of real wages – is offset by the demand stimulus. The introduction of migration, however, results in an increase in the labour supply in the RUK and a reduction in the Scottish labour supply, and this additional supply side constraint exacerbates the loss of competitiveness in this region.

4.3 Simulation results – CO2 trade balance

Just as the CGE model allows us to examine the adjustment of the economy in response to the initial demand shock, it also allows us to examine the pollution content of trade

[12] Lisenkova et al (2007) explores the macroeconomic impacts of demographic change in Scotland in a CGE context, and similarly finds that a tightening of the labour market will have adverse consequences for employment, growth and competitiveness in the Scottish economy.

flows between Scotland and the rest of the UK. We do this by recreating the interregional environmental IO table in each period using the CGE model results for all economic variables, computing the Type II inverse and applying the base year Leontief output-pollution coefficients. Note that the assumption of a Leontief fixed proportional relationship between outputs (in quantities/real units) and emissions is not required in CGE modelling (see Turner, 2002, for a review), nor, as noted above, is our current assumption of Leontief technology in production of the Scottish and RUK local composite commodities. These assumptions are applied for simplicity at this stage (but will be relaxed in future applications and development of the AMOSRUK framework).

Table 7 shows the new environmental trade balance between Scotland and the RUK in the first period when the shock is applied. Table 8 shows the percentage difference from the 1999 Type II base given in Table 1. The first thing to note is that there are changes throughout the table, in contrast to the IO case (Table 5) where only emissions in Scotland and RUK supported by ROW export demand changed. This reflects the fact that both prices and quantities are determined endogenously in the CGE framework, and that the former also change, due to the presence of an active supply side. This in turn induces further changes in local intermediate and final demands, as well as export demand for production in both regions, and both elements of Scotland's CO2 trade balance (emissions embodied in interregional exports and imports to and from RUK) change. In this first period, Figure 6 has already shown that RUK exports to Scotland fall initially (due to the increase in RUK prices) and this is reflected in the reduction in RUK emissions supported by Scottish final demand. Scottish exports to RUK, on the other hand, rise from the outset (to meet increased intermediate and final consumption demand – see Figure 13) and so do Scottish emissions supported by RUK final demand. The composition of trade flows changes. This is due to the exogenous demand stimulus being focussed in the RUK Primary, Manufacturing and construction sector, with the corresponding Scottish sector receiving the largest demand stimulus from RUK (1.624%). The Electricity, Gas and Water Supply sector receives the smallest RUK export demand stimulus in period 1 (0.698%). However, given the relative emissions intensity of this sector, the emissions in this sector supported by RUK export demand to ROW rise by 2.81%.

Table 9 shows the adjustment of Scotland's CO2 trade balance with RUK over the 75 periods modelled. As both Scottish imports from and exports to RUK (Figures 6 and 14) rise the positive impact on the trade balance narrows, but Scotland's CO2 deficit with RUK is reduced overall, due to the larger boost in Scottish exports to RUK and the change in the composition of interregional trade.

Note that while the Quasi IO case comes closest to the IO case by period 75 both in terms of the boost in economic activity and the estimated increase in total UK regional and national CO2 emissions is much smaller, due to the change in composition of activity (Tables 5 and 10). However, we have shown above that this model configuration may overestimate the boost to activity in response to the initial demand stimulus. In the Bargaining case, where real wages also changed in response to the shock, reducing the size of the GDP stimulus in both Scotland and RUK, and in the Flow migration case, where the presence of migration worked to counteract the extent of the stimulus to the Scottish economy, Scottish imports from RUK fall throughout the period modelled, while exports to RUK still increase (but to a lesser extent than in the Quasi IO case). Tables 11 and 12 show the CO2 trade balance in period 75 in these two cases. In both these cases the change in total regional and national emissions is considerably lower than in the IO or Quasi IO cases (Tables 5 and 10), as would be expected, given the more limited increase in activity. In terms of the UK's commitment to reduce/limit CO2 emissions generation, the Flow Migration outcome is the most positive, with the lowest increase in national CO2 generation (0.98% compared to 1.02% in the Bargaining case). This actually involves a reduction of 0.77% in total Scottish emissions as a result of the initial demand stimulus in RUK, but as explained in Section 4.2.6 above, this involves a contraction in activity in the Scottish economy.

The greatest reduction in Scotland's CO2 trade balance with RUK is observed in the Bargaining case. Here the pollution embodied in exports to RUK rises by more (1.74%) in Period 75 than in the Flow Migration case (0.61%), which offsets a slightly bigger reduction in emissions embodied in imports from RUK.

However, as noted above, one of the key benefits of using CGE analysis to inform policy is that we can examine the adjustment path. With IO analysis, we move from one equilibrium to another, with no explanation of the transition process. We have seen here that, in the case of this demand shock, convergence to long-run equilibrium can take a significant number of years, much more than the UK Treasury's stated 10-year time horizon for the analysis of regional policies. Figure 13 shows the change in the CO2 trade balance over the 75-year period modelled. While the ranking of the three configurations in terms of the size of the CO2 trade balance is the same throughout the whole period, the gap between each one changes significantly. Figure 15 illustrates how the absolute change and level of the CO2 trade balance is very similar under the 3 CGE model configurations over 10-year period that policymakers may initially be most interested in, and Figure 16 shows the percentage change in the pollution embodied in gross interregional trade flows between Scotland and RUK. If we consult Figures 6 and 13, we can see that only a portion of the adjustment in trade flows is achieved within this timeframe, and in Quasi IO case, there is a qualitative shift, with the change RUK exports to Scotland becoming positive after around 17 years. Therefore, without access to a full CGE analysis, or relying only on the type of IO results computed in Section 2.2, policymakers concerned with the impact of changes in economic activity on consumption-based measures of UK emissions would lacking important information.[13]

5. Summary and conclusions

There is currently a great deal of interest at the national and regional levels in the UK, and internationally, in accounting for carbon emissions using consumption based measures, such as carbon footprints. In this paper we argue that, while IO is a powerful accounting tool in this respect, if there is a need to model the impacts of marginal changes in activity, the IO modelling framework is limited due to its assumption of a passive supply (or demand) side, and silence on prices (or quantities). Instead we propose that interregional IO accounting frameworks be used as a database in developing more flexible CGE models, which share the main strengths of IO in terms of a multi-sectoral, system-wide framework, but permit more theory-consistent modelling of both supply and demand-side behaviour. We illustrate our argument by comparing

[13] Due to lack of appropriate data, we do not attempt a full consumption-based measure of UK emissions (including pollution embodied in imports from ROW); rather we focus on allocating total UK emissions (under the production accounting principle) to regional consumption demands (using the consumption accounting principle). However, the same broad lessons learned from the analysis presented here would apply to a full consumption-based accounting and modelling exercise.

the results of introducing a positive demand stimulus in the UK economy using both IO and CGE interregional models of Scotland and the rest of the UK. In the case of the latter, we demonstrate how alternative specifications of supply-side behaviour at the regional and national levels affect model results, including the impact on the interregional CO2 'trade balance'. We also show how the CGE framework can be used to track the path of the adjustment of the economy and key indicators (including the CO2 trade balance) over time.

However, we qualify our numerical results on three counts. First, the demand shock introduced is somewhat blunt and unrealistic. CGE models can be used both for more focussed policy analysis (of both supply and demand side disturbances or policy instruments) and to compare results under different theoretical perspectives (as we have done here by configuring our model to represent different stylised versions of labour market configurations that are common in the labour market and regional macroeconomic literature). Second, as explained in McGregor et al (2008) our interregional IO and SAM data for the UK incorporate estimated and experimental data that may distort model results. Third, the 3-sector, 2-region national framework is likely to be too highly sectorally (and perhaps spatially) aggregated for analysis of environmental issues. We aim to address all of these issues in future research. The intention of this paper has been to bridge the gap between IO accounting analysis of the very important issue of pollution embodied in trade flows and interregional CGE modelling analysis, which, to date, has been mainly applied at a more global level, and not, to our knowledge, to the analysis of the trade in embodied pollution.

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Appendix 1. Alternative visions of the labour market.

Quasi IO

The first, 'benchmark', scenario incorporates fixed real wages in both the Scottish and RUK economies. There is no interregional migration of the labour force, so that regional employment is determined solely by regional labour demand. Increased employment is met by increased regional labour market participation, with no change in real wages, so neither region suffers adverse competitiveness effects generated specifically through the labour market as export demand expands, for example. The nominal wage might change but only in response to changes in the regional consumer price index (CPI). Capital fixity dictates supply restrictions, so that marginal costs and prices rise in the short run if output expands. Over time, however, investment optimally adjusts capital stocks, relaxing capacity constraints, and for a demand shock the economy ultimately operates like an extended conventional Input-Output (IO) system (McGregor et al, 1996).

Regional Bargaining

The second simulation scenario involves a set-up where population is fixed in each region as before, but differs from the Quasi IO configuration in that wages are now determined by a bargaining process. The particular bargaining function adopted is the econometrically-parameterised relationship identified by Layard et al (1991):

$$\ln\left[\frac{w^I}{cpi^I}\right] = \beta^I - 1.113\ln u^I \qquad \text{(A1)}$$

where:
w is the nominal wage rate
cpi is the consumer price index
u is the unemployment rate
β is calibrated to ensure that the model replicates the base year data set, and
the I superscript indicates the region.

In both regions, real wages reflect the tightness of the regional labour market, measured as inversely related to the regional unemployment rate. Thus a rise in employment leads to an increase in the regional real wage and a reduction in competitiveness. This configuration is intended to reflect the notion of a conventional 'wage curve' operating at the level of the region[14].

Flow Migration

The third model scenario involves real wage bargaining at the regional level, as in the previous Bargaining set-up, but also introduces interregional migration to allow for population adjustment. Migration flows in one period serve to update the population

[14] As in Blanchflower and Oswald (1990). More recently, they and others have found additional evidence of an inverse relationship between regional unemployment rates and wage rates – see Blanchflower and Oswald (1994, 2005) and Montuenga et al (2003).

stock in the next period. The Scottish rate of in-migration is positively related to the Scottish/RUK ratio of the real consumption wage and negatively related to the Scottish/RUK ratio of unemployment rates, in the spirit of Harris and Todaro (1970)[15]. The specific form of this equation is derived from the Layard *et al* (1991) econometrically parameterised interregional migration function:

$$\ln\left[\frac{m^S}{L^S}\right] = \delta - 0.08\left[\ln u^S - \ln u^R\right] + 0.06\left[\ln\left[\frac{w^S}{cpi^S}\right] - \ln\left[\frac{w^R}{cpi^R}\right]\right] \qquad \text{(A2)}$$

where:
m is net-inmigration
L is population
δ is a calibrated parameter that ensures zero net migration (the equilibrium condition) for the base year data, and
S and R indicate Scotland and the rest of the UK respectively.

In this set-up, the presence of migration allows for a unified national labour market: an increase in regional demand lowers regional unemployment and increases the real wage, inducing migratory flows into that region. In long-run equilibrium, the presence of migration re-imposes the original ratio of regional wage and unemployment rates. In this scenario, the population constraint works only at the national level; migration eases labour market pressures for one of the two regions.

[15] Harris and Todaro (1970) suggests that in-migration will occur to a local area if (among other factors): wages increase, unemployment decreases or job creation increases, thereby increasing expected income in that area. Treyz *et al* (1993) provides further analysis relating to internal migration.

Tables

Table 1. The CO_2 Trade Balance Between Scotland and RUK (tonnes, millions) - Type II Input-Output

	Pollution supported by:						
	Scottish Govt	Scottish Capital	Scot-ROW	RUK Govt	RUK Capital	RUK-ROW	Total regional emissions of CO2
Pollution generated in:							
Scotland	11.3	4.3	14.6	5.7	5.1	8.0	48.9
RUK	8.1	6.3	10.8	144.5	117.9	228.0	515.5
Total (UK) emissions supported by	19.3	10.6	25.4	150.1	122.9	236.0	564.4
Environmental trade balance:							
Scot pollution supported by RUK final demand	18.8						
RUK pollution supported by Scot final demand	25.2						
Scotland's CO2 trade balance	-6.4						

Table 2. Sectoral Breakdown of the Scot/ RUK Inter-regional IO System

Scot/RUK sector		IOC
1.	PRIMARY, MFR and CONSTRUCTION	1-84, 88
2.	ELEC, GAS and WATER SUPPLY	85-87
3.	SERVICES	89-123

Table 3. Percentage change in key variables in response to a 10% increase in ROW export demand to the RUK Primary, Manufacturing and Construction sector

	Output		Value-added		Employment		Direct CO2 emissions	
	Base (£million)	% change	Base (£million)	% change	Base (FTE, thousands)	% change	Base (tonnes, millions)	% change
Scotland:								
PRIMARY, MFR and CONSTRUCTION	52471	0.99%	17134	0.99%	483	0.99%	12.4	0.99%
ELEC, GAS & WATER SUPPLY	5047	1.52%	1508	1.52%	14	1.52%	16.3	1.52%
SERVICES	83723	0.81%	43982	0.81%	1334	0.81%	9.6	0.81%
HOUSEHOLDS	40415	0.87%					10.7	0.87%
Total Scotland			62624	0.87%	1832	0.86%	48.9	1.10%
RUK:								
PRIMARY, MFR and CONSTRUCTION	506584	4.46%	198046	4.46%	5581	4.46%	145.4	4.46%
ELEC, GAS & WATER SUPPLY	42067	2.91%	12896	2.91%	142	2.91%	128.9	2.91%
SERVICES	1031837	1.90%	504567	1.90%	16754	1.90%	109.0	1.90%
HOUSEHOLDS	453771.00	2.63%					132.3	2.63%
Total RUK			715508	2.63%	22477	2.54%	515.5	3.06%
Total	2215914	2.60%	778132	2.49%	24309	2.41%	564.4	2.89%

Table 4. Post-shock CO_2 Trade Balance Between Scotland and RUK (tonnes, millions) - Type II Input-Output

	Pollution supported by: Scottish Govt	Scottish Capital	Scot-ROW	RUK Govt	RUK Capital	RUK-ROW	Total regional emissions of CO2
Pollution generated in:							
Scotland	11.3	4.3	14.6	5.7	5.1	**8.6**	**49.4**
RUK	8.1	6.3	10.8	144.5	117.9	**243.8**	**531.3**
Total (UK) emissions supported by	19.3	10.6	25.4	150.1	122.9	**252.3**	**580.8**
Environmental trade balance:							
Scot pollution supported by RUK final demand	**19.3**						
RUK pollution supported by Scot final demand	**25.2**						
Scotland's CO2 trade balance	**-5.9**						

Table 5. Post-shock CO_2 Trade Balance Between Scotland and RUK (% change from base) - Type II Input-Output

	Pollution supported by: Scottish Govt	Scottish Capital	Scot-ROW	RUK Govt	RUK Capital	RUK-ROW	Total regional emissions of CO2
Pollution generated in:							
Scotland	0.00%	0.00%	0.00%	0.00%	0.00%	6.72%	1.10%
RUK	0.00%	0.00%	0.00%	0.00%	0.00%	6.92%	3.06%
Total (UK) emissions supported by	0.00%	0.00%	0.00%	0.00%	0.00%	6.91%	2.89%
Environmental trade balance:							
Scot pollution supported by RUK final demand	2.88%						
RUK pollution supported by Scot final demand	0.00%						
Scotland's CO2 trade balance	-8.41%						

Table 6: Simulation set-ups

	Population	Regional Wage Setting	
		Scotland	**RUK**
Quasi IO	Fixed at the regional level	Fixed real wage	Fixed real wage
Regional Bargaining	Fixed at the regional level	Bargaining	Bargaining
Flow Migration	Fixed at the national level	Bargaining	Bargaining

Table 7. Post-shock CO_2 Trade Balance Between Scotland and RUK (tonnes, millions) - CGE period 1 (Quasi IO)

	Pollution supported by: Scottish Govt	Scottish Capital	Scot-ROW	RUK Govt	RUK Capital	RUK-ROW	Total regional emissions of CO2
Pollution generated in:							
Scotland	11.3	4.3	14.3	5.6	5.1	**8.3**	**48.9**
RUK	7.9	6.1	10.4	143.4	116.8	**233.5**	**518.2**
Total (UK) emissions supported by	19.2	10.4	24.7	149.0	121.9	**241.8**	**567.0**
Environmental trade balance:							
Scot pollution supported by RUK final demand	**19.0**						
RUK pollution supported by Scot final demand	**24.5**						
Scotland's CO2 trade balance	**-5.5**						

Table 8. Post-shock CO_2 Trade Balance Between Scotland and RUK (% change from base) - CGE Period 1 (Quasi IO)

	Pollution supported by: Scottish Govt	Scottish Capital	Scot-ROW	RUK Govt	RUK Capital	RUK-ROW	Total regional emissions of CO2
Pollution generated in:							
Scotland	-0.09%	0.05%	-1.84%	-0.34%	0.23%	3.04%	-0.08%
RUK	-1.60%	-2.37%	-3.92%	-0.78%	-0.93%	2.43%	0.51%
Total (UK) emissions supported by	-0.72%	-1.39%	-2.72%	-0.76%	-0.88%	2.45%	0.46%
Environmental trade balance:							
Scot pollution supported by RUK final demand	1.26%						
RUK pollution supported by Scot final demand	-2.79%						
Scotland's CO2 trade balance	-14.63%						

Table 9. Post-shock CO_2 Trade Balance Between Scotland and RUK (% change from base) - CGE adjustment (Quasi IO)

	Period/year after demand disturbance introduced: 1	5	10	15	20	30	50	75
Environmental trade balance:								
Scot pollution supported by RUK final demand	1.26%	1.58%	1.84%	2.03%	2.21%	2.62%	2.94%	3.06%
RUK pollution supported by Scot final demand	-2.79%	-2.34%	-1.84%	-1.48%	-1.20%	-0.70%	-0.33%	-0.23%
Scotland's CO2 trade balance	-14.63%	-13.78%	-12.59%	-11.75%	-11.16%	-10.41%	-9.90%	-9.83%

Table 10. Post-shock CO_2 Trade Balance Between Scotland and RUK (% change from base) - CGE Period 75 (Quasi IO)

	Pollution supported by: Scottish Govt	Scottish Capital	Scot-ROW	RUK Govt	RUK Capital	RUK-ROW	Total regional emissions of CO2
Pollution generated in:							
Scotland	-0.06%	0.93%	-0.10%	-0.60%	2.34%	6.09%	1.21%
RUK	-0.47%	0.55%	-0.50%	-0.50%	2.38%	6.43%	3.24%
Total (UK) emissions supported by	-0.23%	0.70%	-0.27%	-0.50%	2.38%	6.42%	3.06%
Environmental trade balance:							
Scot pollution supported by RUK final demand	3.06%						
RUK pollution supported by Scot final demand	-0.23%						
Scotland's CO2 trade balance	-9.83%						

Table 11. Post-shock CO_2 Trade Balance Between Scotland and RUK (% change from base) - CGE Period 75 (Bargaining)

	Pollution supported by: Scottish Govt	Scottish Capital	Scot-ROW	RUK Govt	RUK Capital	RUK-ROW	Total regional emissions of CO2
Pollution generated in:							
Scotland	0.01%	0.01%	-1.64%	-0.03%	0.27%	3.91%	0.18%
RUK	-1.52%	-1.52%	-3.18%	-0.77%	-0.51%	3.48%	1.10%
Total (UK) emissions supported by	-0.63%	-0.90%	-2.30%	-0.74%	-0.48%	3.50%	1.02%
Environmental trade balance:							
Scot pollution supported by RUK final demand	1.74%						
RUK pollution supported by Scot final demand	-2.23%						
Scotland's CO2 trade balance	-13.84%						

Table 12. Post-shock CO_2 Trade Balance Between Scotland and RUK (% change from base) - CGE Period 75 (Flow migration)

	Pollution supported by: Scottish Govt	Scottish Capital	Scot-ROW	RUK Govt	RUK Capital	RUK-ROW	Total regional emissions of CO2
Pollution generated in:							
Scotland	-0.31%	-1.45%	-2.70%	-1.20%	-0.79%	2.76%	-0.77%
RUK	-0.90%	-2.06%	-3.54%	-0.74%	-0.42%	3.54%	1.15%
Total (UK) emissions supported by	-0.56%	-1.81%	-3.06%	-0.76%	-0.44%	3.52%	0.98%
Environmental trade balance:							
Scot pollution supported by RUK final demand	0.61%						
RUK pollution supported by Scot final demand	-2.32%						
Scotland's CO2 trade balance	-10.89%						

Table 13. Post-shock CO_2 Trade Balance Between Scotland and RUK (% change from base) - CGE adjustment (alternative visions of the labour market)

	Period/year after demand disturbance introduced: 1	5	10	15	20	30	50	75
Scotland's CO2 trade balance								
Quasi IO	-14.63%	-13.78%	-12.59%	-11.75%	-11.16%	-10.41%	-9.90%	-9.83%
Bargaining	-15.00%	-14.86%	-14.42%	-14.06%	-13.93%	-13.84%	-13.84%	-13.84%
Flow migration	-15.00%	-14.50%	-13.59%	-12.78%	-12.31%	-11.58%	-11.03%	-10.89%

Figures

Figure 1
RUK GDP: % Change from Base

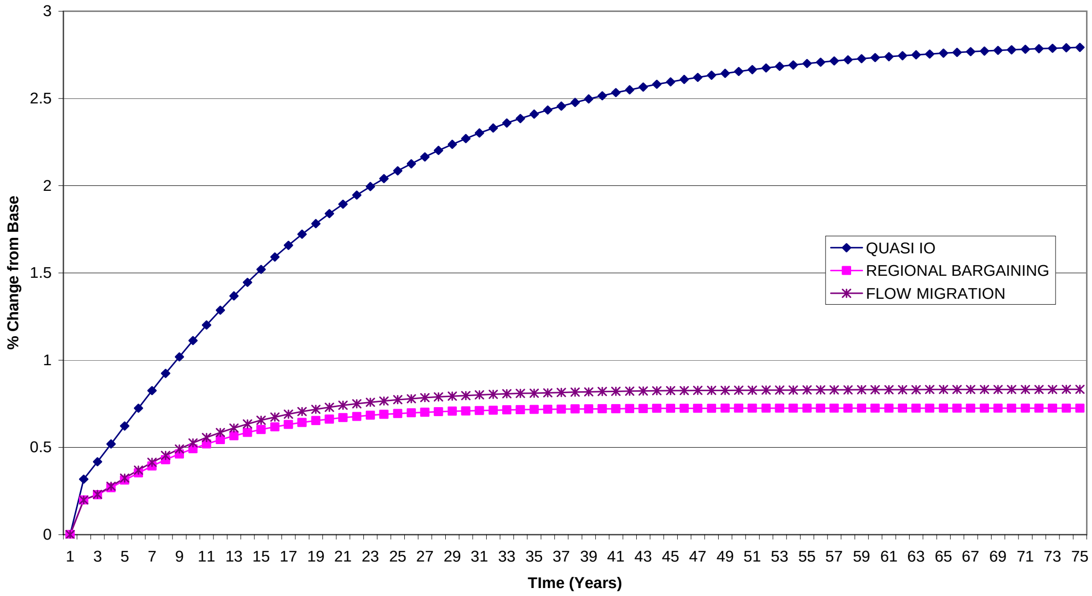

Figure 2
RUK CPI: % Change from Base

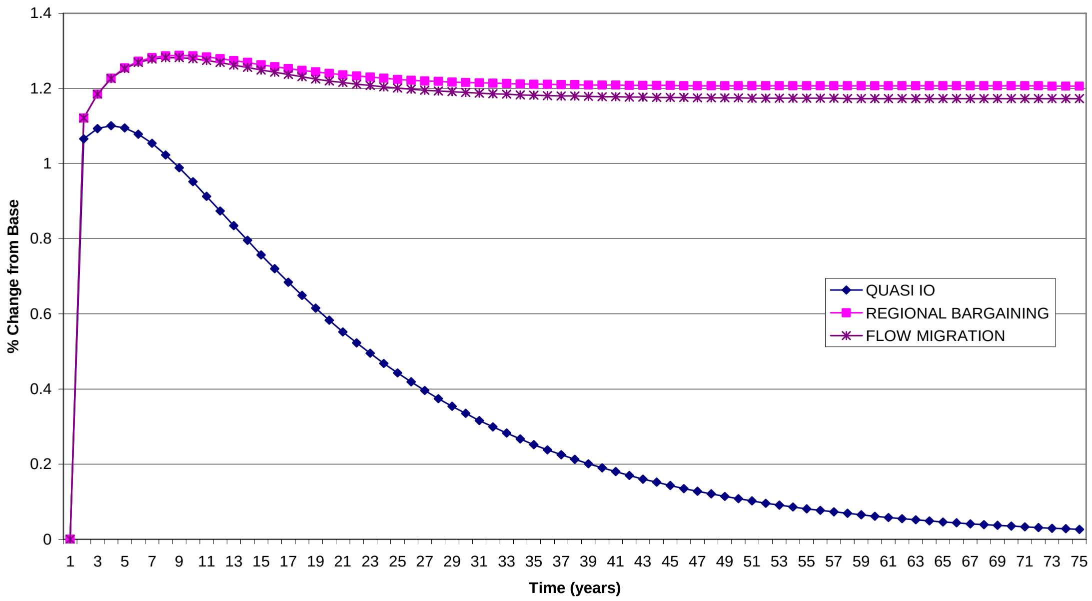

Figure 3
RUK Nominal Wage: % Change from Base

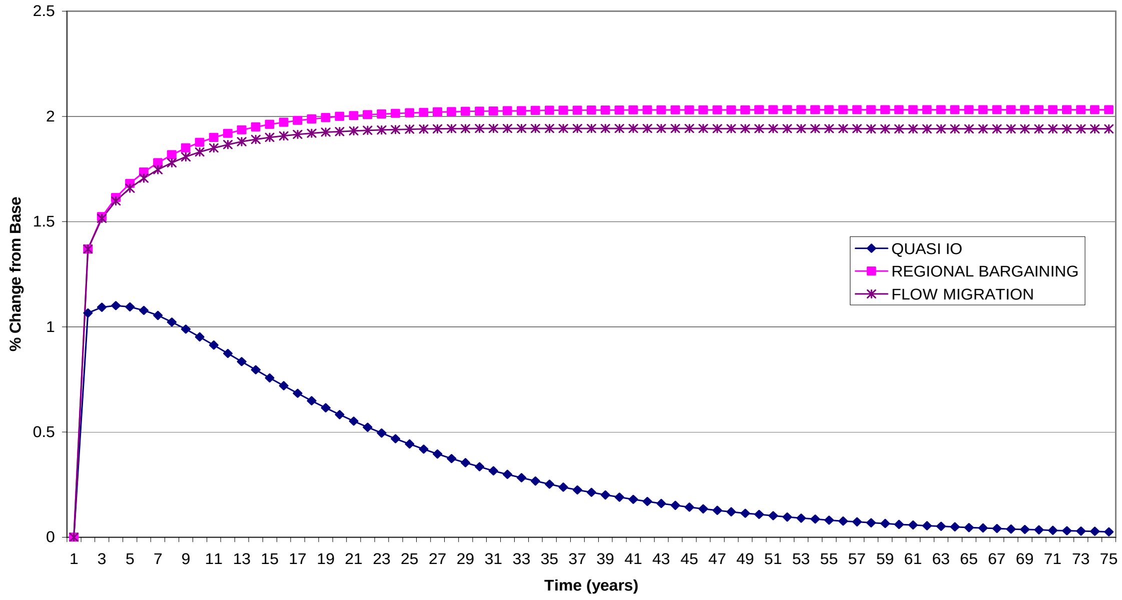

Figure 4
RUK Total Employment: % Change from Base

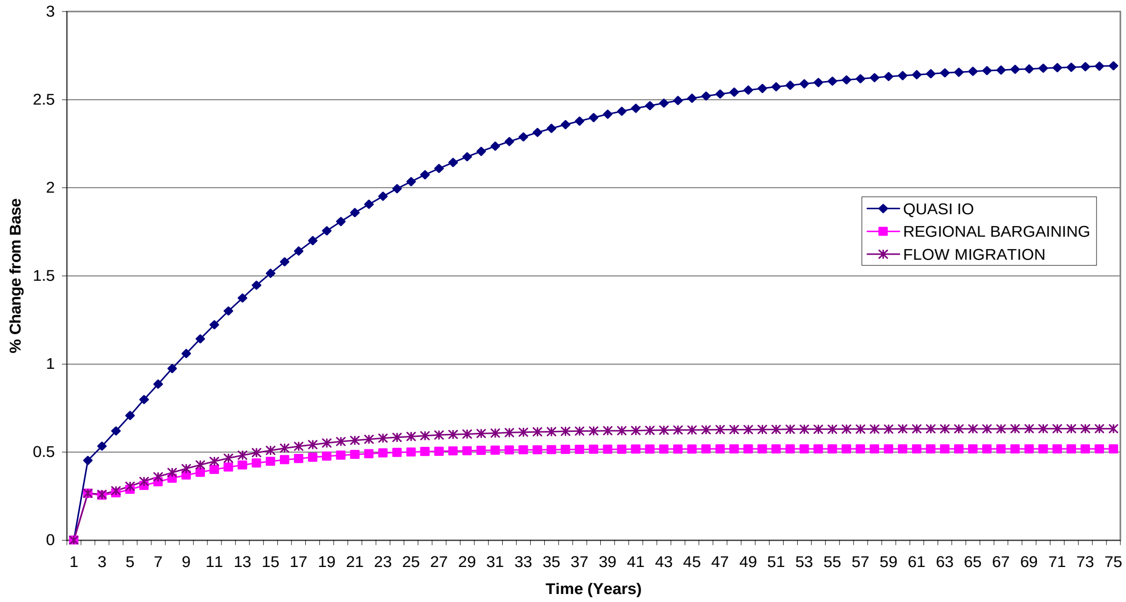

Figure 5
RUK Real Wage: % Change from Base

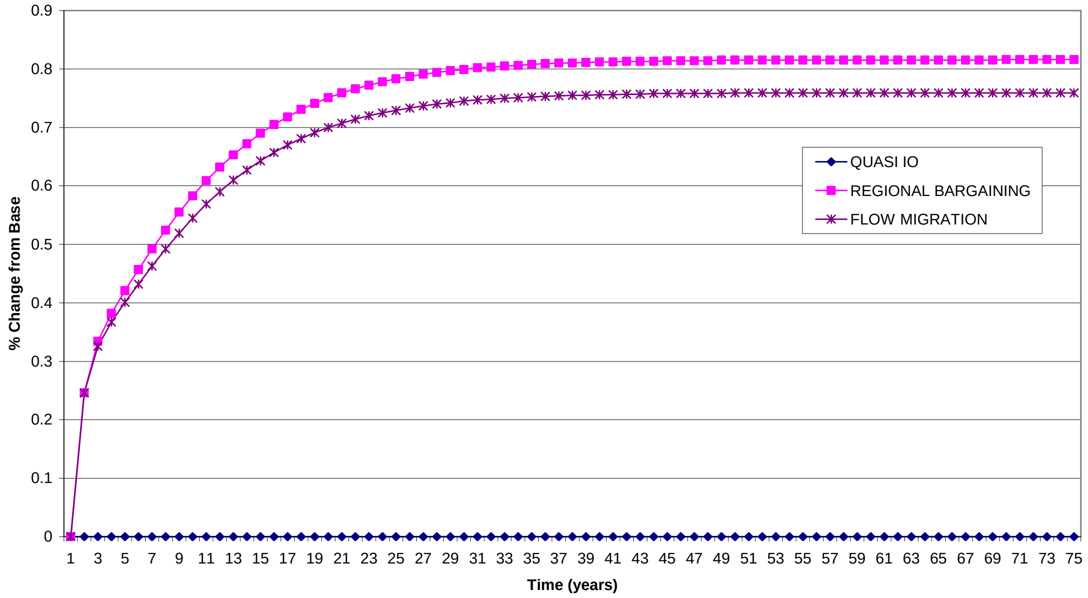

Figure 6
RUK Exports to Scotland : % Change from Base

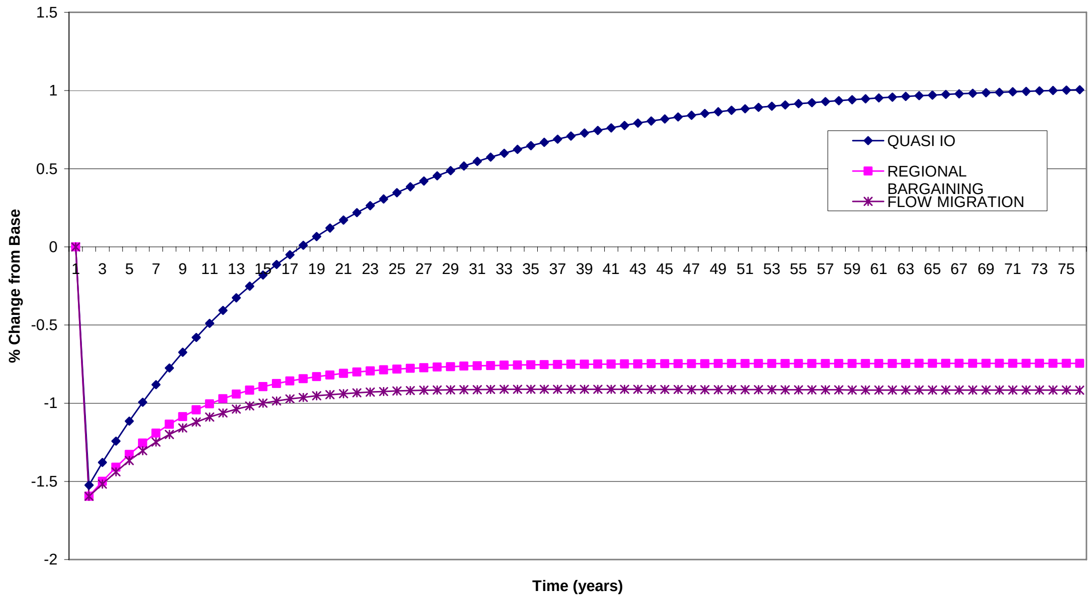

Figure 7
RUK Exports to Rest of the World: % Change from Base

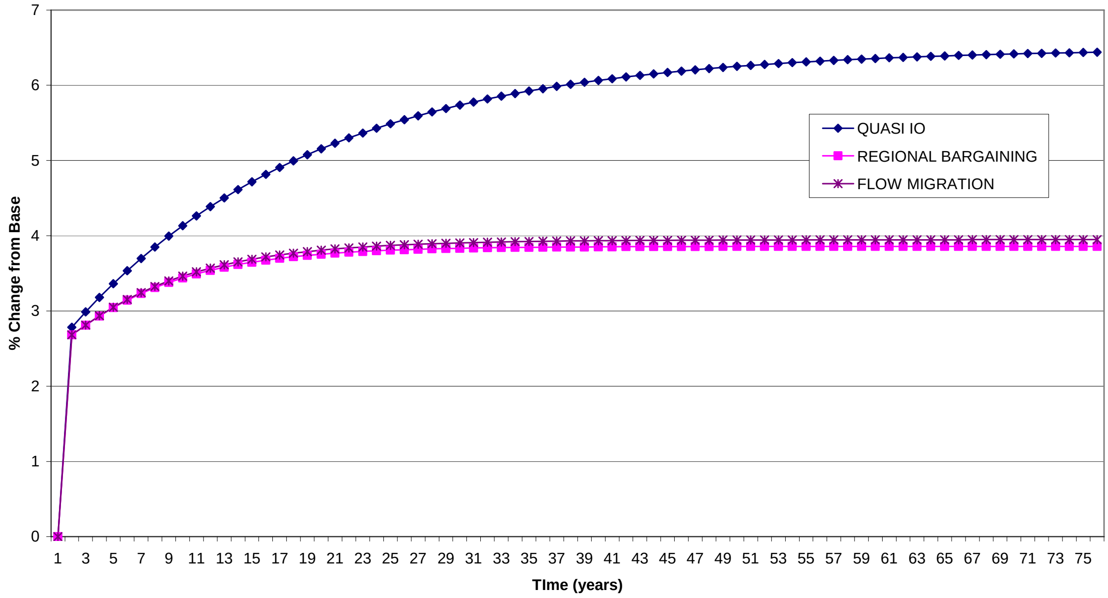

Figure 8
Scottish GDP: % Change from Base

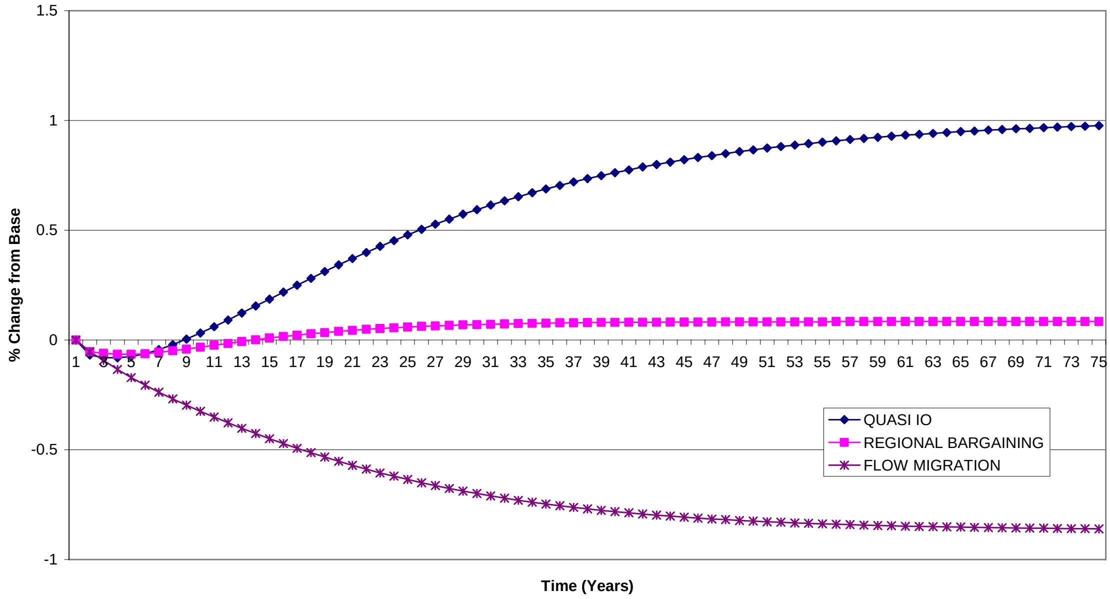

Figure 9
Scottish CPI: % Change from Base

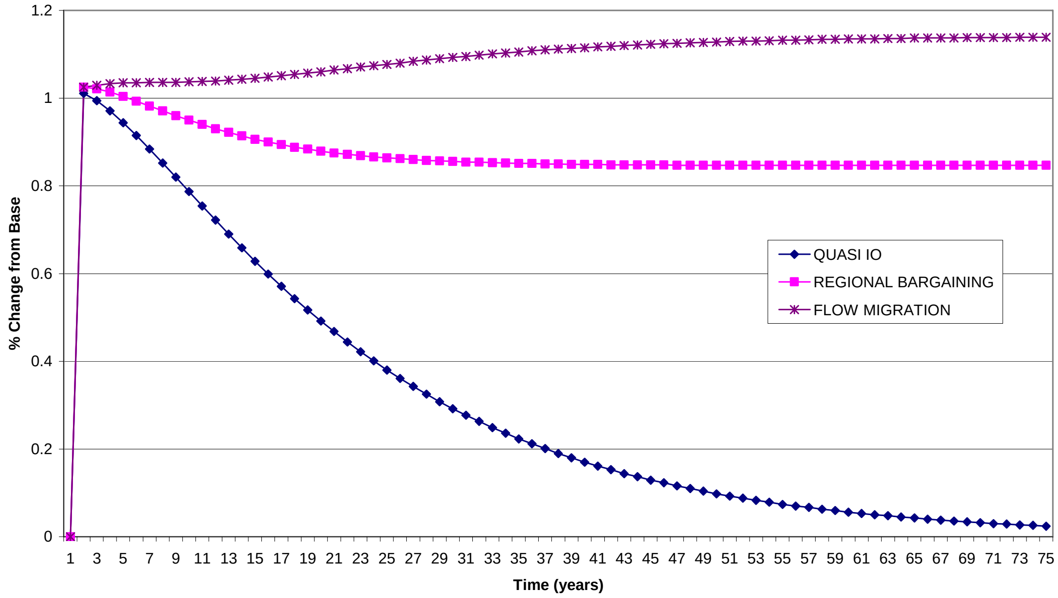

Figure 10
Scottish Nominal Wage: % Change from Base

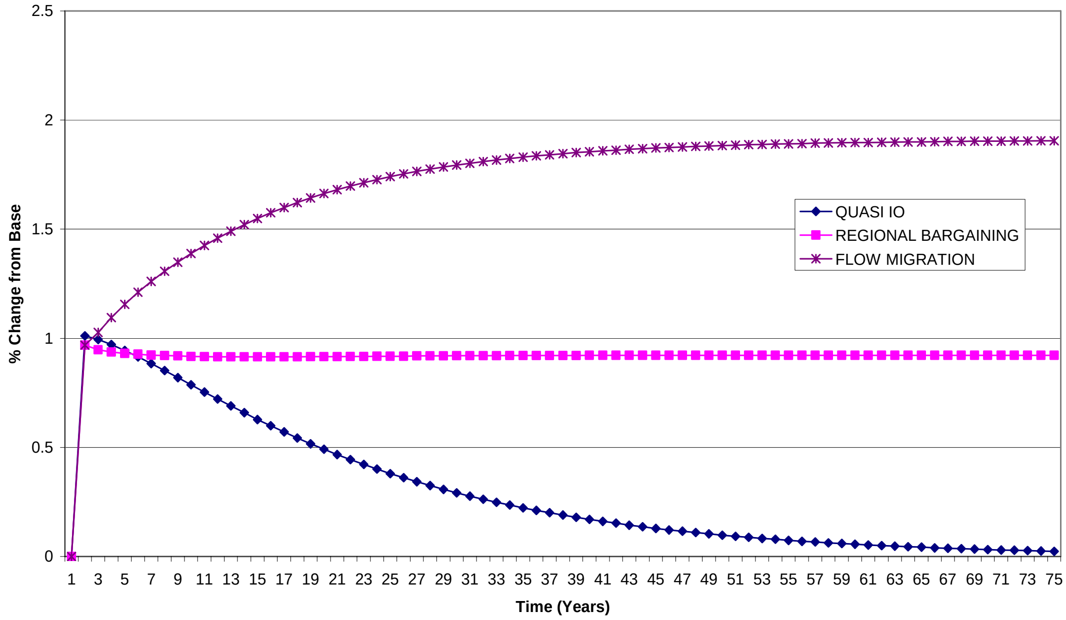

Figure 11
Total Scottish Employment: % Change from Base

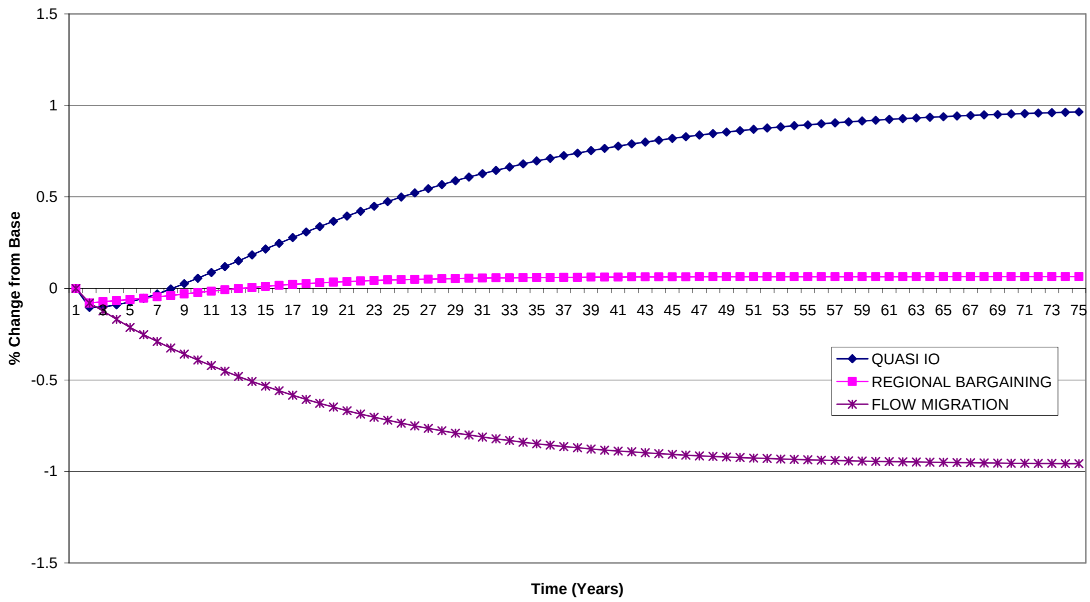

Figure 12
Scottish Real Wage: % Change from Base

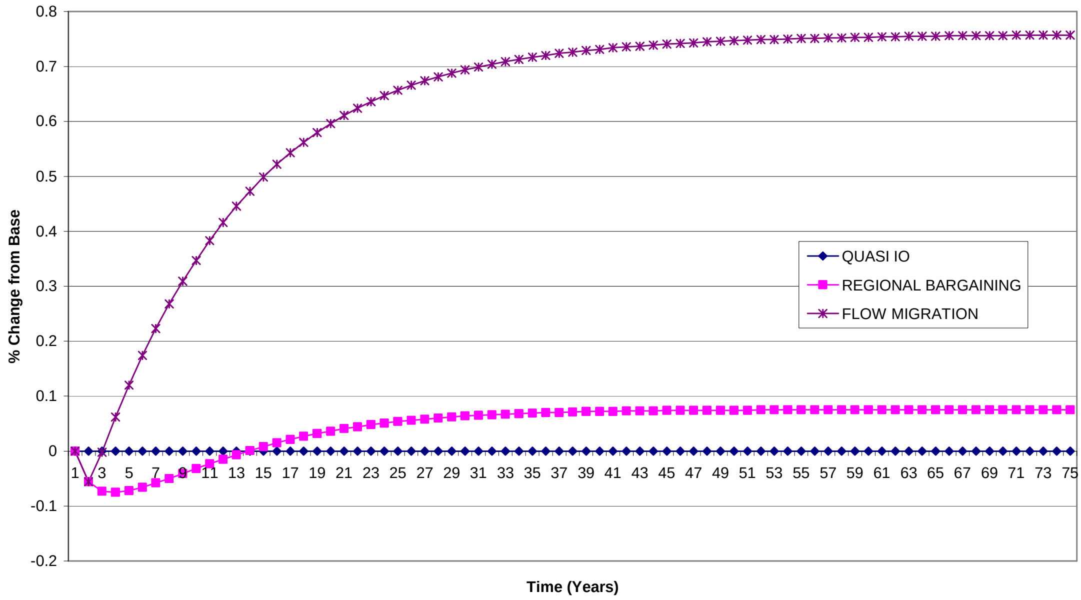

Figure 13
Scottish Exports to RUK: % Change from Base

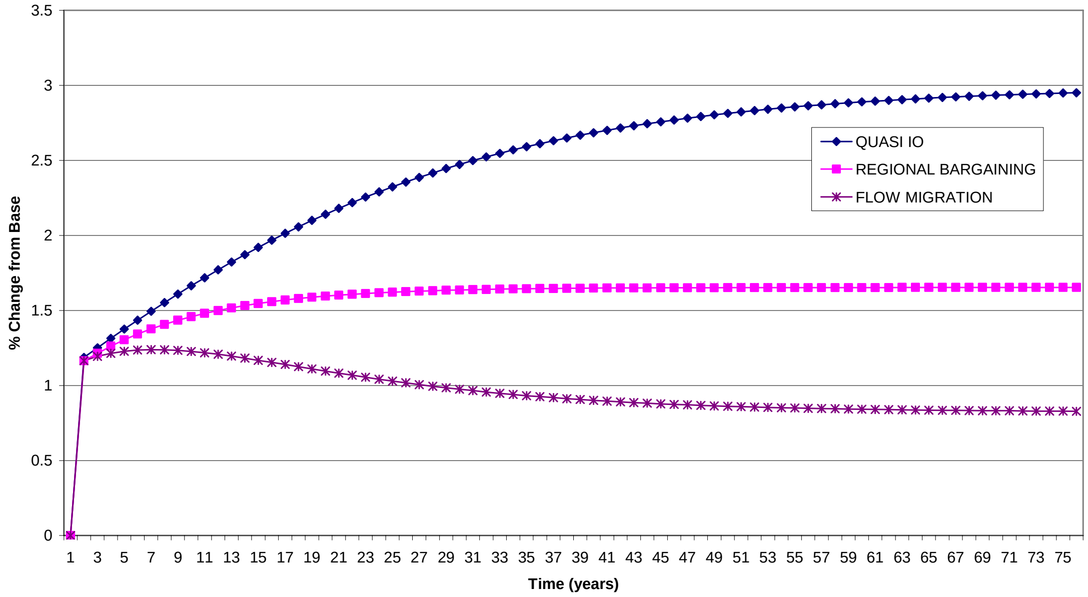

Figure 14
Scottish Exports to ROW: % Change from Base

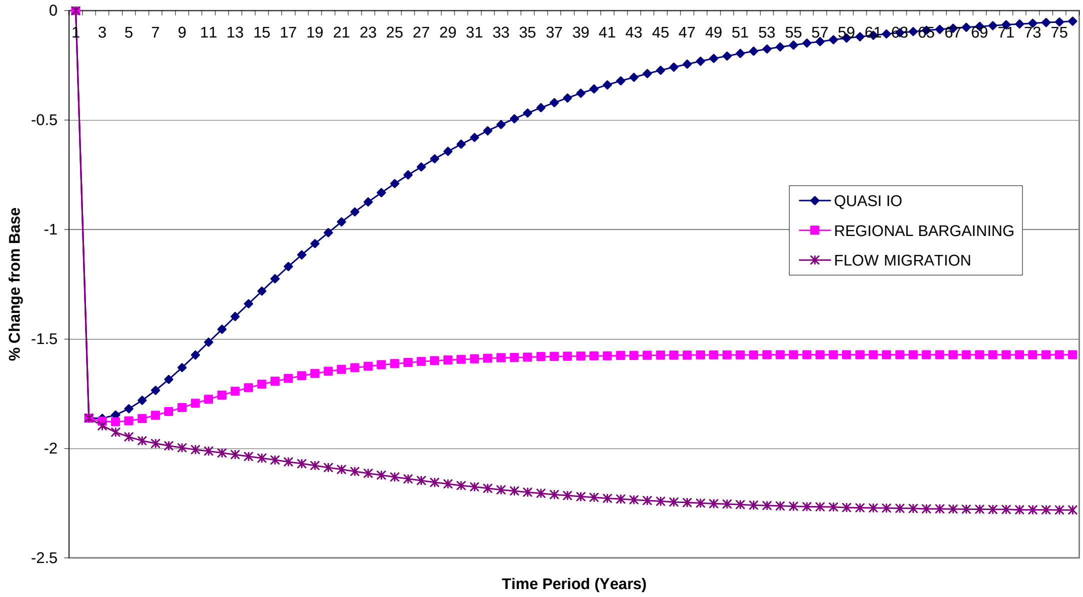

Figure 15 Scotland's CO2 trade balance with RUK in the 10 years following the demand shock

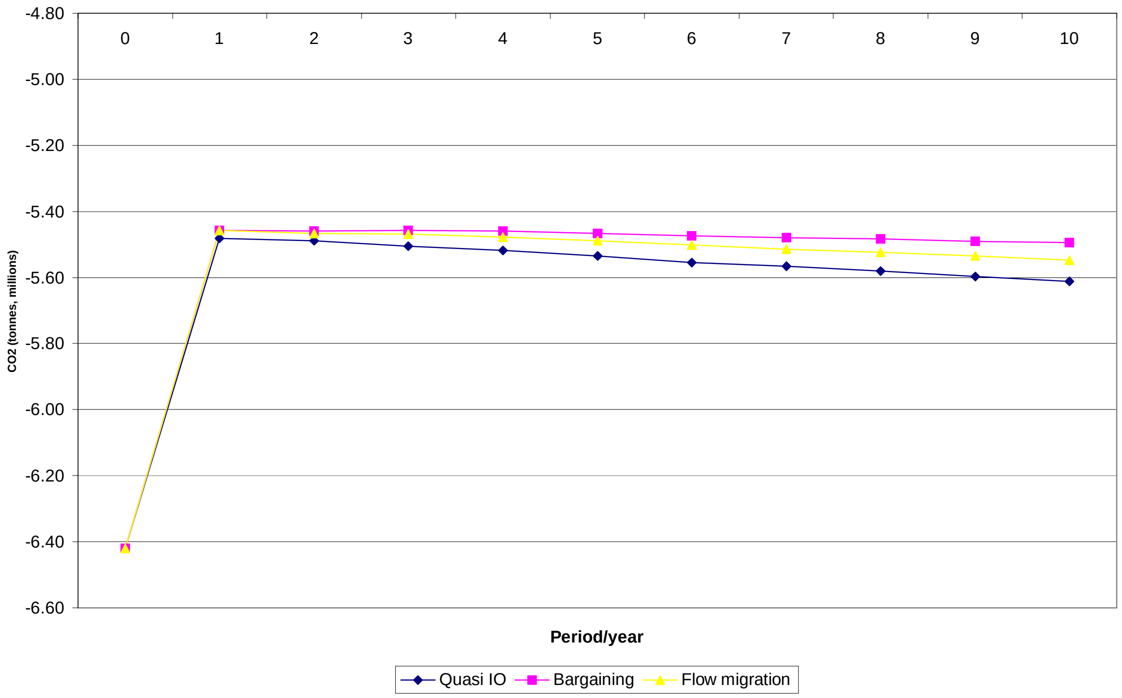

Fig 16 - CO2 embodied in gross interregional trade flows between Scotland and RUK in the 10 years following the demand disturbance