Report on the evidence for net job creation from policy support for energy efficiency and renewable energy: An appraisal of multi-sectoral modelling techniques

September 2012

Grant Allan
Kim Swales
Fraser of Allander Institute, Department of Economics, University of Strathclyde

Michelle Gilmartin
Division of Economics, Stirling Management School, University of Stirling

Peter McGregor
Department of Economics, University of Strathclyde

Commissioned by the UK Energy Research Centre's (UKERC) Technology and Policy Assessment theme, led by Sussex Energy Group (SPRU) and Centre for Energy Policy and Technology (Imperial College).

About UKERC

The UK Energy Research Centre, which is funded by Research Councils UK, carries out world-class research into sustainable future energy systems. It is the hub of UK energy research and the gateway between the UK and the international energy research communities. Our interdisciplinary, whole-systems research informs UK policy development and research strategy.

About the Technology and Policy Assessment theme of UKERC

The Technology and Policy Assessment (TPA) function was established to meet demand from policymakers, industry and other stakeholders for independent, policy-relevant assessments that address key issues and controversies in the energy field.

Contents

1. Introduction

The global response in the face of man-made climate change has focused on reducing the environmental impacts of human activities. The Kyoto protocol, for instance, was the world first global agreement to reduce emissions of greenhouse gases. Much of the focus of national and international emissions reduction strategies has been on the way in which energy is produced and used in economies. Evidence suggests that much of the economic development since the industrial revolution has gone hand in hand with increased demand for and use of energy. This has typically over the last century increased demand for and use of energy from fossil fuels, such as from coal, oil and gas. The ways in which energy is produced and used can have significant impacts on greenhouse gas emissions. Solutions proposed for reducing emissions during energy production include renewable energy technologies, while energy efficiency has been proposed as the key mechanism through which energy use is reduced.

Renewable energy technologies, which derive energy from natural phenomena such as wind, tides and sunlight, typically emit zero emissions during their operational phase, and offer the potential to significantly alter the relationship between energy production and use, and emissions[1]. An important consideration however is the economic impact of moving from fossil-fuel to renewable energy technologies. Currently, renewable forms of electricity generation are typically more expensive than fossil-fuel derived generation from a private (i.e. investor) perspective (Heptonstall, 2007; Allan *et al*, 2011a). From a social perspective however, there is an economic case to subsidise renewable technologies due to externalities. At the same time, it has been argued that there may be economic opportunities from developing renewable technologies either through finding export markets for new technology developments (Carley *et al*, 2011; Allan *et al*, 2008) or through reducing dependency on imported primary energy. It becomes crucial therefore for the appropriate design of policy that these potential economic benefits from renewables can be quantitatively estimated. A number of modelling approaches have been used to quantify the impact of renewables technologies, either through the construction or operational phases, and to analyse the impacts of changes in the electricity generation mix.

Reducing emissions by targeting energy use has focused on improving energy efficiency. This could mean either improving the efficiency of energy use in production– thereby reducing the energy intensity of production – or in the consumption of energy by end-consumers (e.g. households). Technological improvements, such as more energy or fuel efficient production techniques, would contribute to industrial energy efficiency enhancements, while consumer

---

[1] Life-Cycle Analysis of energy technologies is a widely used method for establishing the emissions "embodied" in particular technologies or activities. This procedure acknowledges the "cradle-to-grave" emissions produced by technologies during their manufacture, installation and decommissioning, and so would reveal positive gross emissions even by renewable energy technologies.

energy efficiency steps could include improved household insulation or vehicle engines with improved "miles per gallon" consumption figures. A significant literature has evolved examining whether energy efficiency improvements do lead to reduced energy demands and reduced emissions (see Sorrell, 2007, for a review of the literature to that point). Much debate has concerned the role that "rebound" and "backfire" effects play in reducing, and potentially offsetting, the energy saving benefits from energy efficiency improvements. Many studies have focused on the direct rebound effect, studying individuals or micro-level behaviours from partial or case-study approaches. A number of multi-sectoral modelling approaches have been employed to examine the economy-wide effect of energy efficiency improvements, particularly Computable General Equilibrium models (see Allan *et al*, 2007 for a review). Multi-sectoral modelling techniques are especially important for examining economic and environmental impacts as the emissions intensities of production can differ hugely across industrial sectors and energy or environmental policy or developments will tend to have impacts on specific parts of an economy, for example large users of energy or sectors with large emissions.

The aim of this paper is to describe three multi-sectoral modelling techniques, and to show how these modelling approaches have been used to quantify the economic impact of renewable energy and energy efficiency developments.

The three techniques are Input-Output (IO), Computable General Equilibrium (CGE) and Macroeconometric studies. Each is firstly detailed in a separate section. In each section we describe the nature and operation of the technique, and identify different types and sub-types (where appropriate). We then consider the data requirements of these modelling approaches and finally discuss what might be considered the strengths and weaknesses of each approach. For each modelling approach we pay particular attention to the ways in which the employment effects are estimated, as employment is arguably the most tangible economic variable.

After sections on each of the three modelling techniques, we address some general questions about their applicability and validity of each approach for understanding the quantitative impacts of renewable energy and energy efficiency improvements.

- *Input-Output (IO)*

Developed by Wassily Leontief (1941)[2], IO is the most widely used multi-sectoral economic modelling technique. It is frequently employed for impact analysis owning to the simplicity of its typical configuration. Modellers require an IO table for the economy under consideration, a potential limitation that has become less problematic over time as nations, and regions, develop their own IO accounts under agreed conventions. The IO accounts show the economy for a given period of time, usually a year, revealing the linkages between sectors (and between

[2] Wassily Leontief (1905-1999) received the 1973 Nobel prize in Economics for "the development and application of the input-output method".

sectors and consumers) in production and use. The most typical use of IO tables for modelling is to evaluate the economy-wide impacts of changes in expenditure on goods and services produced in the economy. The assumptions necessary for IO modelling might be considered as restrictive: for example, this approach typically assumes that the economy is demand-driven and supply reacts entirely passively. The models are also linear, meaning that any change in sectoral output will generate the same percentage change in sectoral employment.

- *Computable General Equilibrium (CGE)*

A CGE model is an analytically consistent mathematical representation of an economy. The basic structure is straightforward – it comprises a detailed database of actual economy-wide data which captures the interdependencies across all sectors in the economy at a particular point in time, and a set of equations describing model variables. This can be considered a more general modelling framework than IO for the estimation of the system-wide impacts of economic disturbances as both supply and demand can be modelled systematically and simultaneously. There are typical features which many CGE models share. However, unlike IO there is not one dominant framework or structure to these models (see Allan *et al*, 2007). This may be because, where these techniques are being used to model real economies, the CGE model builder will attempt to reflect particular features of the economy under consideration in his/her model, or to reflect a particular feature of interest, e.g. energy production, and omitting the same level of detail on other aspects (e.g. non-energy production). Among other things, the way in which the labour and capital market is modelled, and the treatment of trade, can be crucial for the results obtained from these models. CGE models have increasingly been used for energy and environmental, as well as economic, modelling.

- *Macroeconometric modelling (MM)*

Macroeconometric models encompass a wide range of models for macroeconomic time series analysis and estimation and inference procedures. The models are used to address a multitude of different issues, including examining the impacts of policy measures; to understand the propagation of policy shocks; or examining the determinants of business cycle fluctuations or economic growth. 'Modern' macroeconometric models are typically dynamic stochastic general equilibrium (DSGE) models. These models were originally developed to study how real shocks to the economy might cause business cycle fluctuations (Kydland and Prescott, 1982). They are now used widely in policy analysis, but particularly for examining the impact of monetary disturbances, where they are able to accommodate, for example, structural shocks, adaptive expectations and real and monetary frictions. The models incorporate rational, infinite-lived, identical households who maximise intra- and inter-temporal utility. They are closely related to CGE models in terms of specification and computation, but in contrast to CGE models, agent maximisation occurs within a stochastic, rather than a deterministic, environment. One important advantage of the stochasticity of the model is that it lends itself to econometric estimation and the fitting of time series data.

2. Input-Output (IO) analysis

2.1 Exposition of nature and operation of IO method[3]

2.1.1 IO theory

Input-Output (IO) analysis requires the use of a set of IO accounts for an economy. These identify the monetary linkages both between production sectors in an economy and between production sectors and consumers of output (both domestic and non-domestic). The IO table gives a "snapshot" of the nature of production and consumption flows in an economy during a specific period of time, usually a year. A schematic of an (analytical) IO table is shown in Figure 1[4]. Column entries describe purchases, either from production sectors or of primary inputs. The row entries represent sales of products and primary inputs to production sectors and final demand categories. All values in an IO table are in monetary units, and shown at basic prices (i.e. net of taxes).

"Final demand categories" show purchases by households, government, capital formation, stocks[5], and exports of the outputs produced by each sector in the economy. The "Intermediate quadrant" shows the flows of spending between production sectors on intermediate inputs. "Primary inputs" will show purchases by local production sectors of non-domestically produced goods and services. These will include imports, taxes, subsidies, wage payments and payments to capital. The number of sectors (*N*) and final demand categories (*K*) can vary with the level of detail at which the table is constructed.

[3] This section draws text from Section 2 of Allan (2011).

[4] Other forms of IO tables, and their availability, are discussed in Section 2.3.

[5] "Capital formation" figures show the level of demand for the output of specific sectors for use in investment, i.e. the addition to existing levels of capital or replacement of depreciating capital stocks. "Stocks" figures show the level of demand for the output of specific sectors for use in stock building by individual sectors, and tend to be small compared to "Capital formation" for annual IO tables.

Figure 1: Schematic layout of an (analytical) Input-Output table

Purchases Sales	Production sectors (n = 1,…,N)	Final demand categories (k = 1,…,K)	Gross output
Production sectors (n = 1,…,N)	Intermediate quadrant	Final demand quadrant	Sectoral gross outputs
Primary inputs (including imports)	Primary input quadrant	Final demand purchases of primary inputs	Gross primary inputs
Gross inputs	Sectoral gross inputs	Gross final demand inputs	

A simple example of an IO table is given in Table 1. This is an aggregation of the IO table for Scotland in 2007.

Table 1: IO table for Scotland in 2007, 3 sector aggregation, £millions except where stated.

£million, 2007	Primary and manufacturing	Utilities and construction	Services	Total intermediate demand	Household	Government	Investment and stocks	Exports	Total final demand	Gross outputs
Primary and manufacturing	8080	2473	3162	13715	4061	1	1282	25726	31069	44785
Utilities and construction	1572	8050	2460	12081	2297	0	9663	3959	15919	28000
Services	4829	2332	28851	36011	35770	28747	2908	25853	93278	129289
Total intermediate inputs	14480	12855	34473	61808	42127	28748	13852	55538	140266	202074
Imports	13751	4776	18103	36630	21611	0	6311	1193	29115	65745
Net taxes on products and production	236	376	4584	5197	7541	0	1186	118	8845	14042
Compensation of employees	10220	5256	46432	61907	0	0	0	0	0	61907
Other value added	6097	4737	25697	36532	0	0	0	0	0	36532
Total primary inputs	30304	15145	94816	140266	29153	0	7496	1311	37961	178227
Gross inputs	44785	28000	129289	202074	71280	28748	21349	56850	178227	380301
Employment (FTE)	263,533	149,567	1,618,834	0						

Reading down the columns of Table 1 we can see that in the year 2007 the "Primary and manufacturing" sector produced an output of £44,785 million. It made purchases of £14,480 million from other industries, it purchased £13,751 million worth of imports, paid net taxes on products and production of £236 million, paid £10,220 million in wage income and had total other value added of £6,097 million. Reading along the row for the same sector, we see that it sold £13,715 million of its output to intermediate demand, with £25,726 million worth of its output going to exports out of total final demand of £31,069 million.

IO tables commonly serve two uses – "attribution" and "modelling". Attribution refers to the use of the IO accounts to assign responsibility for all output (and variables which can be linked to production, such as employment, value added or pollution) in the economy to final demand categories for the goods and services produced in the area (examples of this include McGregor *et al*, 2004[6]).

In their second use, the inter-industry linkages detailed in the IO table can be used to model the economy-wide impact of new (exogenous) final demand disturbances. These disturbances might be either sector-specific – e.g. increased demand for the output of a particularly sector- or relate to changes in the levels of a final demand category – e.g. reduced government expenditure.[7]

With regards to both accounting and modelling, the key equation of IO analysis is:

$$X = (I - A)^{-1} F \qquad \text{Equation 1}$$

where X is a vector of sectoral gross outputs, F is a vector of final demands for sectoral outputs and $(I - A)^{-1}$ is a matrix known as the Leontief inverse. The Leontief inverse is calculated in the following way: I is an identity matrix, while the A matrix comprises elements $a_{i,j}$, which are the technical coefficients representing the purchases by sector j from sector i, expressed as a fraction of total gross inputs to sector j ($a_{i,j} = \frac{x_{i,j}}{X_j}$). Using Equation 1, we can see how (changes in) exogenous final demand determine (changes in) sectoral output through the Leontief inverse matrix. The derivation of Equation 1 is shown in Appendix A.

The column sums of the Leontief inverse matrix give the additional impact on economic activity (i.e. output) of a unit change in the final demand for that sector's output. This is referred to as that sector's "output multiplier", as it shows the impact on total activity of an initial change in

---

[6] This uses a two-region IO for Scotland and the rest of the UK to assign responsibility for pollution in each region to final demand categories in each region.

[7] Other uses of analytical IO tables for modelling, such as "supply-driven" multipliers are discussed in Section 2.2.

demand. Multipliers use the inter-industry linkages provided by an IO table to quantify the aggregate “knock-on” effect of changes in demand for individual sectors (Miller and Blair, 2009).

The calculated “output multiplier” will be larger than one as total output will be higher by the unit increase[8] *plus* the additional activity in other sectors of the economy which are required to provide inputs to the now expanded sector (and those sectors which have expanded to produce inputs to the sectors which are linked to the sector which saw the initial increase in demand). Through this “rippling” process, the sectoral multiplier will reveal the difference between the initial demand disturbance and the aggregate effect.

IO analysts might use “Type 1” and “Type 2” multipliers, which make different assumptions about the treatment of additional wage income and consumption spending. Under Type 1, the multiplier takes account of the interlinkages between sectors to calculate the total effect on sectors’ outputs (and hence inputs) of an increase in final demand for a specific sector. The difference between the Type 1 multiplier and the “direct” effect (i.e. the initial stimulus) is termed the “indirect” effect. Any increase in output, and employment, observed under a Type 1 analysis assumes that the increased level of wage income does not act as a further demand stimulus to activity. The Type 1 process is sometimes referred to as the “open” model (Miller and Blair, 2009).

With Type 2, the household sector is included alongside the production sectors. This requires the extension of the A matrix with an additional row and column relating to the household sector. Each labour expenditure row element is the relevant sector’s purchases of labour divided by the sector’s gross output, while column elements are households purchases of goods and services divided by total wage income. This procedure is referred to as “closing” the model with respect to households, usually shortened to refer to a “closed” model. Under this setup, increased wage incomes are retained in the economy through increased household consumption, and so Type 2 multipliers will be greater than Type 1. The difference between Type 2 and Type 1 multipliers is termed the “induced” effect.

The impact on other variables – i.e. employment, value added, and income – can be straightforwardly estimated through the calculation and use of alternative “multipliers”. As Miller and Blair (2009, p. 250) note, “an analyst is more likely to be concerned with the economic impacts of new final demand as measured by jobs created, increased household earnings, value added generated, etc., rather than simply gross output by sector”. In Appendix 1, we show, for the three-sector example introduced above, a number of Type 1 and Type 2 multipliers, derived from the Scottish IO tables.

---

[8] We refer to increase, but the same method would apply if the change in final demand for sector’s outputs was negative.

Sectoral "employment-employment multipliers", for example, reveal the impact on (aggregate) employment to changes in (direct) employment in a specific sector[9]. The impact on employment of changes in final demand can be found by augmenting Equation 1 with a vector of sectoral employment-output coefficients (e_i):

$$\Delta E = e_i (I - A)^{-1} \Delta F \qquad \text{Equation 3}$$

2.1.2 Modelling existing activities in IO

IO analysis has been used to evaluate the employment impacts of existing activities and of new activities. The IO framework can be used for both of these. However the approach used is different as in the first case the activity is already represented in the IO table, while in the second case this is not the case.

A set of IO accounts can be used to demonstrate the economic importance of existing activities for other sectors and incomes in the economy under consideration (e.g. Lehr *et al*, 2008). For renewable energy, this typically surveyed firms active in delivering, constructing, operating renewable energy technologies, or service industries ancillary to the operation of renewable technologies – e.g. surveying, testing – and then used this information to construct the row and column values for a sector representing the renewables industry.

A conventional approach for showing the importance of individual sectors on economic activity is to undertake a procedure called "hypothetical extraction". In this procedure, the row and column for an individual sector in the Leontief inverse is set to zero. With Equation 1, if we set the row for sector *i* to zero, we can solve for the level of output consistent with this new equilibrium. This will always be lower than the initial level of output in the economy as, we are in essence assuming that any local demand for this sector that was produced locally is now imported – and so doesn't create additional knock-on effects on the local economy. The reduction in activity caused by the "extraction" of the sector will be due to its own scale (the direct effect), its links with other sectors in the local economy (captured in the indirect effect), and its importance as a sector employing staff and paying wages (captured in the induced effect).

Studies of the direct employment in the renewables energy industry have been done in the past – see, for example, Blanco and Rodrigues (2009) – and this information would be a crucial requirement for calculating the indirect and induced effects on employment of the renewable energy sector. With sectoral direct employment figures and sectoral employment-employment multipliers (as discussed above), the analyst could estimate the indirect and/or induced effects on employment through the economy. One should note that the accuracy of both the direct

---

[9] An employment-employment multiplier of 3.0 for instance, would mean that five new jobs created in a particular sector could be expected to create fifteen jobs across the economy.

effects and the knock-on (indirect and/or induced) effects will be crucial for the estimation of the contribution that activities make across the economy. For the appropriate multipliers to be used, the analyst should as closely as possible match the activity that is represented to the appropriate sector in the IO table for the same economic area, otherwise results could be misleading. We highlight one example of this – in the context of the electricity sector – in Section 2.1.4 and Section 2.4.

2.1.3 Modelling new activities in IO

Several approaches have used IO frameworks for evaluating the economic impacts of new renewable energy developments. Firstly, one might estimate the (annual) operational expenditures associated with a new energy technology, and input these as the disturbance to final demands for specific sectors in the IO table. This is the approach employed in several studies (e.g. Caldes *et al*, 2009; Swenson, 2006). The analyst should be careful to ensure that the expenditures are as closely matched as possible to the appropriate activity which could see an increase in demand for its output. It is important that the results from the construction phase of the project be identified separately from those for the annual expenditures of the project. Once the annual expenditures related to a particular development have been identified, Equation 2 can be used to calculate the impact on annual employment resulting from these expenditures. This would give the change in employment consistent with the new equilibrium level of output where final demand is now permanently higher than previously.

A second approach is to incorporate the new renewable energy development into the IO table for the economy under consideration by specifying its (annual, if the IO table is for a year) forward and backward linkages explicitly, and “adding” a new sector to the economy which represents the new development (e.g. Just, 1974; Gowdy and Miller, 1991; Herendeen and Plant, 1981; Blair, 1979; Casler and Hannon, 1989; Kulišić *et al*, 2007; Low and Isserman, 2009). To include the new industry in the technical coefficient matrix means that a new row and column describing the pattern of sales and purchases by the new sector must be identified. Calculating new economic output for the augmented IO table, the difference between base year levels of output and new levels can be credited to the addition of the new technology.

$$X^{*} = (I - A^{*})^{-1} F^{*} \qquad \text{Equation 3}$$

Where A^{*}, F^{*} and X^{*} are the augmented A matrix, final demand matrix and gross output matrix respectively. The impact of the new sector on output is therefore ($X^{*} - X$). This approach typically only focuses on the operational phase of the energy development. The results obtained would then be the new level of economic activity – including employment – which would be consistent with the operation of the new renewable energy facility. The linkages between the development and the economy would therefore be crucial for the modeled result, as would the potential for the new activity to displace existing economic activity (Allan, 2011).

The impact of the construction phase could be estimated separately using IO (e.g. O'Herlihy, 2007). This would typically involve using the sector specific expenditures and appropriate multipliers to estimate the system-wide impacts of these expenditures. One should be careful not to add the economic impact from the operational phase of a project to the construction phase. The impact of the operational phase would be the recurring impact on the economy under consideration in each year of the project, while the construction phase is typically much shorter.

An additional benefit of IO models for examining the operational, as well as construction, phases of renewables is that the modeller must make explicit the assumptions about the domestic supply chain, i.e. linkages, of the technology. For nascent technologies these links may be difficult to construct, but this adds transparency to the analysis.

As we shall discuss in Section 2.4, IO models typically assume a "demand-driven" system, in which supply is passive. This would mean that there would not be assumed any displacement of existing activity as a result of new activity moving to the region. This may be a reasonable assumption in some areas or time periods, e.g. with high unemployment placing limited pressure on wage rates following a demand-shock. However, this assumption is certainly not always appropriate. Such constraints could be accommodated within a CGE framework, as will be discussed later. A central issue is that the purpose of introducing a new (low carbon) technology to reduce carbon emissions, then this would necessitate replacing existing (more carbon intensive) activity, which means calculating a net effect.

Displacement in product markets, rather than factor markets, has typically been a feature of some recent studies for biofuels, for example (see Allan, 2011). The question in these papers has been how much additional agricultural activity is created by a new biofuels facility locating in a region. If the analyst assumes that all the feedstocks used are additional, i.e. would not have been produced without the operation of the biofuels facility, then the economic impact is greater than if the biofuels facility diverts feedstocks from existing consumption, perhaps for exports, to being used locally. Some studies of biofuels facilities have made the assumption that total production of the feedstock remains unchanged (e.g. Swenson, 2006; Low and Isserman, 2009) from initial levels when a new biofuels facility locates in a region. There will consequently be no additional modeled impacts from expansions in the agricultural sector. Macdonald and Swales (1991), for example, show how the traditional regional multiplier method can be accommodated to incorporate possible price and income effects in product markets. Their example focuses on a supermarket which displaces consumption from local shops, but lowers prices, increasing real incomes for households.

The impacts of expenditure switching, i.e. spending in one pattern rather than a different one, can be evaluated simply within an IO framework. For renewable projects, a study of this sort was carried out by Verso Economics (2011). This reported that the employment effects in

Scotland of policy to support renewables probably resulted in a small net loss of jobs, while at the level of the UK, "for every job created in renewable energy, 3.7 jobs are lost" (p. 1).

2.1.4 Electricity sector in IO

The impact of changes in final demand for the output of existing sectors is relatively straightforward to model. For the analysis of renewables – a common application for IO analysis – the sectoral classification typically fails to separately identify a single sector called "renewable energy". The generation of electricity from renewable sources, for instance, will typically be part of (and so combined with) the rest of the electricity sector. Further, this electricity sector includes generation of electricity as part of its activities – transmission, distribution and supply of electricity are also included within this sector. Other activities which relate to renewable energy will typically be part of existing sectors in the IO accounts, for example, wire and cable production, surveying or manufacturing of generators. O'Herlihy (2007) examined the sectoral elements involved in the supply chain for an onshore wind farm project, and used IO analysis to calculate the additional knock-on impacts of spending in each element on the Scottish economy. None of the multipliers that were used in this paper related to the "Electricity" sector, as spending was purely on the pre-operational (i.e. testing, construction and installation) stages of the wind power development.

Analysts concerned with the impacts of changes in the scale of electricity production must be careful when using "off-the-shelf" multipliers for the electricity sector for another reason. Where the IO tables are constructed with a single electricity sector, this relates to all activities – i.e. generation, transmission, distribution and supply – related to electricity in the economy. The single multiplier for the "Electricity" sector masks the potential for there to be quite different linkages between electricity generation technologies and the economy, and so potentially significant different multipliers. Allan *et al* (2007) and others (Rodrigues and Linares, 2010; Sue Wing, 2008) have identified that bottom-up surveys of generation technologies can allow these to be "extracted" from the non-generation elements of the electricity sector. When these differences in inputs to each generation technology are accounted for, there can be quite significant differences in the estimated multipliers for generation technologies.

2.2 Identification of different types and sub-types of IO models

2.2.1 Interregional

Miller and Blair (2009) note that much of the initial IO analysis was focused on national economies, an increasing amount of work using IO has focused on sub-national (i.e. regional) economies. This has lea to single-region applications of IO analysis and analysis of many regions using inter-regional analysis. These applications are typically of regions within the same country, with inter-national IO analysis uncommon. Among the benefits of extending to more than one region include taking account of feedback and spillover impacts of development in one area, particularly where there are trade links in production or factor markets between regions. For example, energy efficiency investments in region A might require materials from region B, and other inputs from region C. Omitting an important trading partner from the analysis could lead to significant underrepresentation of the total economic impacts of changes in one particular region. Spillover and feedback effects from changes in one regions activity could have important impacts outside the region.

In order to operationalise an inter-regional IO table however requires a set of IO accounts for the area. Various methods exist to create these tables where they are not already available. The first starting point for creating these tables would be the national table for the economy in which the specific focus region is located. Several issues which must be considered in obtaining a regional (or interregional) IO table from the national table. One is the potential differences in production structure (as given by the $a_{i,j}$ coefficients) between firms in the same sector at the national and regional level. A second is the extent to which sectors in regions will be able to source inputs for production from within the regional economy. A smaller region, for example, will typically be more dependent on trade with other regions (outside the regional IO account) than a larger economy, and multipliers will typically be smaller (other things being equal) for regions that have smaller economies.

2.2.2 Supply-side IO

Supply-side modelling was introduced to use the IO table to examine the impact of changes in supply of goods and services on total activity, rather than the conventional demand-side perspective of IO. Under supply-side modelling changes in the availability of factors of supply (e.g. labour and capital) cause changes in economic activity. One example would be where there were strikes in particular sectors, with employees withdrawing their labour. This perspective was introduced (Ghosh, 1958) in part to model (government imposed) supply restricted economies (Miller and Blair, 2009, p. 548). Its applicability has been criticised by Oosterhaven (1980; 1988; 1989) while Dietzenbacher (1997) has proposed its use as a prices rather than quantities model.

Liu *et al* (2009) uses the Leontief price model to examine the impact of changes in the price of electricity on production prices across the Chinese economy. Their particular focus is on the indirect energy and emissions content of household consumption. They separately and together simulate scenarios in which 1) electricity prices are increased by 1% and 2) intermediate electricity use is decreased by 1% through electricity saving policies. By their calculations, “if the increase in electricity prices is combined with a reduction in electricity usage [i.e. if the electricity price increases and intermediate demand for electricity reduces], there would be a tiny decrease in production prices and consumption prices, and an increase in household income, in which situation, both economic and environmental goals would be practically accomplished” (Liu *et al*, 2009, p. 3203).

2.2.3 Social Accounting Matrix (SAM) applications

A more detailed set of accounts than an IO table, called a Social Accounting Matrix, might been used to examine the economic impacts of disturbances in an economy from a wider perspective, although both approaches share similarities such as linearity. SAM analysis, as with IO, begins with a set of accounts describing the nature of production in a particular period, however, unlike IO, a SAM offers a complete picture of all incomes and expenditures within that area. An IO table, for example, has particular focus on incomes related to production activities, but does not include incomes and expenditures which are not related to production in that period. For instance, the wage payments given in an IO table are only those related to production in that same period. Although wage income will typically be the largest element of household income for many households, other forms of income – not linked to production – will also be received in each period. These could include public or private pensions, other benefits such as unemployment insurance, or receipts of income from abroad.

Taking account of all incomes, and not just those linked to production activities, can also be done alongside disaggregation of the elements of final demand to get a fuller picture of the incomes and expenditures of particular categories. This has been particularly a focus for the analysis of the economic impacts of demographic or poverty-related policies as the household final demand category might be disaggregated by age of household or income of household. SAMs have a history of being used to evaluate the distributional impacts of policies on poverty and household groups, and so would provide a dataset perhaps more suited to exploring issues such as fuel poverty, for example, than an IO system.

Although IO studies are more common some recent work has used SAMs to examine the impact of renewable energy technologies (e.g. Swenson and Eathington, 2006; Allan *et al*, 2011). These studies acknowledge that using IO tables to quantify the impact on activity could be misleading as these focus exclusively on intermediate input and employment linkages between technologies and the economy. We saw above that Type 1 analysis captures inter-industry linkages, and Type 2 analysis extends this to capture wage payments. Further "closing" the IO model with respect to capital formation has been done in the past, but is much less common. Both papers address specifically the treatment of returns to capital (i.e. ownership profits), and the additional impact on economic activity if these are retained (and spent) within that same economy. An application using a CGE model to explore the additional local impacts of renewable projects retaining income in the local economy has been carried out by Phimister and Roberts (2012). SAM modelling, as in these examples, requires the use of the same assumptions as IO modelling, and these are discussed in Section 2.4.

2.3 Data requirements and availability for OECD and UK

As will be clear from our above discussion, IO analysis requires an (analytical) IO table for the economy under consideration, be it a regional or national or international economy. The availability of the analytical IO tables necessary for IO analysis is mixed. In this section we begin by summarising the availability of IO databases for OECD countries, before focusing on tables for the UK, including Scotland and Wales (which have single-region IO tables).

The OECD Input-Output tables database contains 39 tables from countries across the world, typically for the year 2005. This database also has tables from around the year 2000 and 1995. The most recent tables for each country are published with 37 sectors separately identified. As mentioned above, different forms of electricity generation, including renewables, are not separately identified in these tables, but are aggregated together with other electricity activities (as well as Gas and Water) in a sector called "Utility".

For the OECD, a report from 2006 noted updates to the methodology used to construct "harmonised" tables for each country of the OECD, and published analytical tables (at a 12 sector aggregation) for 27 OECD countries (and 8 non-OECD countries) from around the year 2000 (Yamano and Ahmad, 2006).

For the UK, in August 2011, National Statistics published a set of IO accounts relating to the year 2005. The accounts were constructed at 122 production sectors and 9 final demand categories.

For Scotland, the Scottish Government has continued the work of the Scottish Office and Scottish Executive, in maintaining the IO accounts for Scotland as part of its ongoing statistical programme. IO tables were first developed for Scotland for 1973 and have been produced fairly regularly since the mid-1970s. In recent years, IO tables for Scotland have been produced by the Scottish Government for the years between 1998 to 2007[10]. Late in 2010, the Scottish Government published consistent IO tables (at current prices in each year) for Scotland between 1998 and 2007 (removing any differences in the methodologies that previous tables had used, so that older tables were consistent with more recent tables). The Scottish Government have a rolling programme of IO development and extension, and are scheduled to publish an IO Table for 2008 in 2012, as the economic accounts move to the most recent Standard Industrial Classification. The published IO tables have 128 production sectors and ten final demand categories[11], allowing for significant sectoral detail both in multipliers and modelling.

The Welsh Economy Research Unit (WERU) has produced IO tables for the Welsh economy over the last fifteen years. The most recent tables date from 2007 (Jones *et al*, 2010). Previous tables relate to 1994, 1996 and 2000. The most recent tables are produced at 88 sectors and 9 final demand categories. Unlike the tables for Scotland, the IO tables for Wales are not produced by

---

[10] The tables and documents relating to these can be found online at http://www.scotland.gov.uk/Topics/Statistics/Browse/Economy/Input-Output.

[11] These are, "Households", "Non-Profit Institutions Serving Households", "Non-resident household expenditure", "Central government", "Local government", "Gross Fixed Capital Formation", "Valuables", "Change in Inventories", "Rest of UK exports" and "Rest of World exports".

government, but are produced by WERU. Within the most recent table, the authors have carried out disaggregation of the electricity sector, so that – as with the examples described above – there are sectors relating to electricity generation (further broken down by technology) and non-generation activities.

For employment, environmental and other extensions, what is necessary is that these variables relevant for these issues can be tied to industrial sectors. Having this allows the IO method to be used to estimate these impacts of changes in economic activity on (non-monetary) effects. Clearly for employment, aggregate employment figures for each sector would be needed before the employment effects can be evaluated.

2.4 Strengths and weaknesses, focusing on employment effects

There are three important assumptions underlying the use of "demand-driven" IO analysis for modelling:

- Fixed technical coefficients and constant returns to scale[12]
- Demand is exogenous
- Entirely passive supply side

The first assumption implies that the inputs used by a sector increase in proportion to any change in the output of that sector. For example, if demand for a particular sector's output increases by 10%, then that sectors demands for each of its inputs (from other intermediate sectors and primary inputs) also increase by 10%. The sector is taken to be characterised by fixed technical coefficients in production, meaning that industries cannot substitute inputs in production, but always purchase inputs in the same proportion as per its column in the IO table[13]. The sectoral output multiplier, for instance, gives the aggregate effect of marginal changes in demand for that sector, but is calculated from the average sectoral purchases[14].

The second assumption requires that any economic disturbance be translated into a change in demand, and that this is exogenous. This might be a changed demand for a specific sectors' output, or a changed level of demand for a specific category of (final demand) expenditure. At

---

[12] Type 2 multipliers in the "closed" model assume fixed coefficients in endogenous – typically, household – consumption. See Appendix A.

[13] An alternative interpretation might be that input prices do not change as a result of the demand stimulus to the sector, such that the optimal production mix does not change from that given by the initial technical coefficients (McGregor *et al*, 1996).

[14] In the "closed" model with households endogenised, changes in demand cause sectoral output and therefore household income to adjust, which leads to corresponding changes in household spending. Changes in household income will cause the purchases by households from each of the industrial sectors in the region to adjust by the same proportionate amount, e.g. a 5% increase in wage income will cause household base year demands for the outputs of each sector to increase by 5%.

no time – aside from in the Type 2 model when household income and spending is endogenous – do the final demands themselves interact with the level of activity in the economy in question. In estimating the employment impacts of changes in exogenous demand, it is crucial that the disturbance is correctly introduced, and takes account of any displaced economic activity, for example.

The final assumption is perhaps central in "demand-driven" IO and SAM analysis. Where demand for a sector's output increases, the demand for inputs to that sector's production increase, raising the demands for all production sectors to expand through their links to the directly stimulated sector, as recorded by the Leontief inverse. In conventional IO modelling treatment, at no point in this "rippling" of additional production is there assumed to be anything preventing the output of any sector adjusting to satisfy the increased demand. There must therefore be no constraints on the ability of sectors to source intermediate or primary inputs (e.g. labour). A further implication of this assumption is that there is no inherent "switching" of resources between sectors in the face of increased demand: no sectors are required to contract in order that other sectors can expand. We have seen above in Section 2.1.4 that displacement effects in factor or product markets can be modeled using IO.

In IO modelling it is assumed that supply reacts passively to demand. That is to say, for all demand increases, these can be accommodated through the expansion of supply at the existing prices. This is consistent with a region or nation which has extensive underutilisation of resources, such as significant underemployment of labour and excess productive capacity. Similarly, in a region which was able to attract labour and capital resources through migration and investment respectively, such supply constraints could be non-binding in the long-run (e.g. McGregor *et al*, 1996).

It is the simplicity of IO that has led to its being the most widely used method of assessing employment impacts (Berck and Hoffmann, 2002). It has been acknowledged, however, that the three assumptions outlined above can make it unsuitable for modelling policies in which relative prices change within an economy (as these are not modelled). Consequently, linear models would not be expected to overstate regional effects in applications to a "small economy with policies that do not affect relative prices" (Berck and Hoffmann, 2002). When relative prices are expected to be changed from their initial levels, it would be beneficial to consider a (more complex) modelling approach such as Computable General Equilibrium (CGE). In the face of demand disturbances – for example, resulting from temporary expenditures on installing renewable energy devices – IO multipliers assume that firstly there are no crowding out effects (since supply is assumed passive) and that impacts happen instantaneously. This suggests that IO analysis might be considered as a special case of CGE in which the above assumptions are imposed.

3. Computable General Equilibrium (CGE) analysis

3.1 The nature and operation of the CGE method

3.1.1 The general model structure of a CGE model

A CGE model is an analytically consistent mathematical representation of an economy. The basic structure is straightforward – it comprises a detailed database of actual economy-wide data which captures the interdependencies across all sectors in the economy at a particular point in time, and a set of equations describing model variables. These equations tend to be neoclassical in spirit: households maximise utility subject to a budget constraint, and firms maximise profits (minimise costs). This gives rise to demand and supply functions, derived in accordance with standard consumption and production theories.

Most CGE models tend to be static, in that they do not incorporate a time element, and model the reactions of the economy at only one point in time[15]. A recent area of progress in CGE modelling relates to the incorporation of "recursive" dynamic properties into the model structure. This involves individual single period (e.g. annual) model equilibria (results) being linked through pre-specified relationships relating to, for example, investment, government borrowing or labour migration. This means that changes in model "flow" variables (e.g. investment, migration or government borrowing) in preceding time periods determine the values of endogenous variables computed in the current time period via their contribution to the model's corresponding "stock" variables (e.g. capital, population, or government debt). Thus the model is solved for each period individually (rather than being solved for each period simultaneously), with period-by-period solutions liked via these predefined relationships relating to how capital is accumulated, or how the population is affected by migration, for example.

A "typical" CGE framework tends to have: two factors of production (labour, which may be disaggregated by skill level, and capital); have a limited number of commodities; and model inter-industry linkages based on an IO table or SAM database. In addition, the assumption of

[15] By static, we mean "comparative static" in that results compare one equilibrium to the next. In contrast, dynamic models explicitly incorporate a time element into the framework (for example by making model agents forward-looking). In doing so, they can be used to model changes over time, and to describe the process of model adjustment over time. For such multi-period dynamic models, all time periods must be solved simultaneously (rather than one period at a time), making the mathematical solution techniques more complex than for static models. Accordingly, there are fewer examples of fully dynamic CGE models in the literature.

‘constant returns to scale’[16] for production technologies is often used to facilitate an equilibrium concept upon which to base the analysis.

The models are solved computationally, with an equilibrium being characterised by a set of prices and level of production across all sectors such that demand equals supply for all commodities simultaneously[17]. The framework is used to estimate how an economy might react to changes in policy or other exogenous influences, and the counterfactual solutions provide quantitative estimates of the impact of specific policies or effects on the allocation of resources and the relative price of goods and factors. For example, the model could estimate numerical results which indicate the impact on variables such as GDP caused by an exogenous (policy) change. The framework also provides qualitative information about the impact of a policy change in that, by means of sensitivity analysis, modellers can assess the importance of key parameter values or key model assumptions by comparing the results from identical policy simulations across models with different assumptions about the configuration of the labour market or the elasticity of substitution between capital and labour, for example. Additionally, the models can provide an indication of the adjustment process (in the case of recursive dynamic or fully dynamic models), and the ability to “rank” alternative policies or policy packages.

In the proceeding sub-sections, we describe in more detail the characteristics of different elements of a ‘classic’ national CGE model. These are by no means the defining characteristics of a CGE model. In fact, a number of factors influence common model features, including the availability of data and solution techniques, but the precise structure of a CGE model is determined largely by the intended use of the model.

3.1.1.1 Households

Households are both consumers and owners of factors of production. They receive income from factor payments in the form of rent on capital and wages (and any other income streams, such as transfer from the government, depending on the number and type of factors included in the model framework). This income is used to pay for households’ consumption of goods and services (and for tax payments or savings, again depending on the exact model description). Consumption generates utility for households, and households decide how much

---

[16] Constant returns to scale implies that a change in all production inputs by x units leads to a change in production output by x units.

[17] Underlying the CGE methodology is the Walrasian general equilibrium structure (Walras, 1926), which is expressed in mathematical terms as a system of simultaneous equations representing market equilibrium conditions, where an equilibrium is characterised by a set of prices and levels of production in each industry such that demand equals supply for all commodities simultaneously. Shoven and Whalley (1992) set out the basic principles in more technical detail.

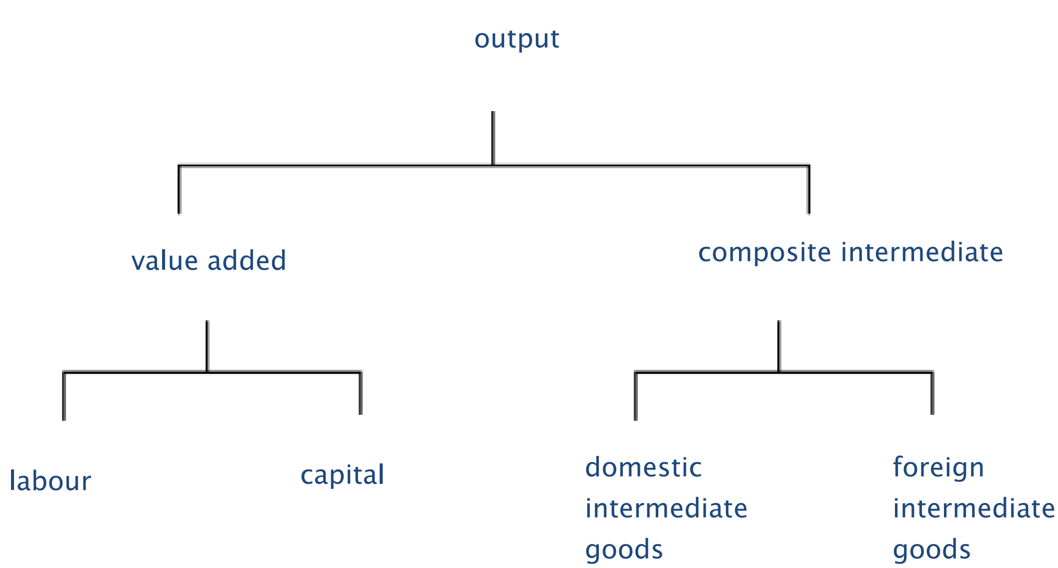
of their income to allocate across goods and services with the objective of maximizing utility subject to their budget constraint. This utility maximization problem is most often posed in terms of a 'representative' household, although some models do disaggregate households' by income level or household type.

3.1.1.2 Producers

In the production sector, there is a set of inputs to production (such as labour, capital and intermediate materials) and a set of outputs (i.e. final goods or services). A designated production function specifies how the economic inputs are combined in order to produce firms' outputs. The production function is therefore a technological relationship, based on an understanding of how production processes occur in practice. The production structure describes how firms make choices over how much of each input to use, and how much output to produce. The standard approach in CGE modelling is to have a multi-level (or "nested") production structure which incorporates both intermediate goods (such as raw materials) and value-added (such as labour) as inputs in the production process. An example of a "nested" production structure is provided in Figure 3.1.

Figure 3.1 describes a production process whereby labour and capital inputs are combined to make a "value-added" input, and domestic and foreign intermediate inputs are combined to make a "composite intermediate input". The value-added and composite intermediate inputs are combined to make a final good. At each level of the production structure hierarchy, an elasticity of substitution can be specified. This describes and quantifies how far producers substitute between inputs at this level in response to changes in relative prices. The "nested" production arrangement is intended to represent realistic production possibilities. In our example in Figure 3.1, consider the case of an increase in the cost of labour. Firstly, capital may be substituted for a relatively more expensive labour input. Further, the increase in the wage will increase the price of value added whereas domestic intermediate goods cannot be substituted as a replacement for labour inputs.

Figure 3.1 An example of a nested two-level production technology structure



Firms are assumed to profit maximise (cost minimise), and they make decisions on how much overall output to produce using the prices of goods and services as market signals[18]. Primary input factors (labour and capital) are purchased from households, and intermediate goods are purchased from other firms. The sales revenues generated from production are used to pay the owners of factors of production and the suppliers of intermediate inputs. The assumption of perfect competition means that no economic profits are made in equilibrium.

3.1.1.3 Government sector

In a CGE model with a government sector, the role of the government is to receive income in the form of taxes and tariffs, to redistribute income in the form of subsidies and benefits, and to purchase goods and services. Unlike the activity of consumers and producers, which is explicitly optimization-based, government activities tend to be used to impose exogenous changes on the model, in the form of policy shocks.

3.1.1.4 Choice of functional form

The selection of utility and production functions is partly determined by the requirements of theoretical consistency and analytical tractability. Whilst the functions are required to meet the standard constraints of a general equilibrium model, such as market clearing and normal profits in all markets (see Section 3.1.1.7 for a discussion of non-neoclassical model closures, including the incorporation of unemployment in equilibrium, for example), they also need to generate production and expenditure patterns that can be easily evaluated at equilibrium. As a result, ‘well-behaved’ functional forms such as the Cobb-Douglas or Constant Elasticity of Substitution (CES) forms are often used.

3.1.1.5 Degree of aggregation

The choice of the level of aggregation is also determined by the purpose at hand, as well as data availability. Even in the case of an abundance of data, there exists a trade-off between using a highly disaggregated data set in order to achieve more detailed model results – for example detailed sectoral employment impacts, versus the associated computational difficulties of doing so, and the complexities involved in interpreting a substantial volume of results.

3.1.1.6 Trade

International or interregional trade may be incorporated into a CGE model, both in terms of trade in intermediate inputs and composite commodity outputs. For intermediate inputs, it is necessary to specify the elasticity of substitution between imported foreign or other region goods and domestic goods. Almost all CGE models incorporate an Armington (1969)

---

[18] In practice, the presence of imperfectly competitive market characteristics, for example market power or bounded rationality (where the rationale and ability of firms to make optimal decisions is affected by time, cognitive or informational constraints), such price signals may be distorted.

assumption for this purpose. This assumption differentiates products by country or region of origin, so that cars produced in Germany, for example, differ from cars produced in the US[19]. Therefore, even in the case of free trade between the economies, world prices for US and German cars do not need to be equal, allowing each country to simultaneously import and export cars. Without this assumption, the existence of perfect competition and homogeneous products would mean that for individual commodities, the economy could only be self-sufficient, exporting-only or importing-only. Such 'law of one price' models are characterised by extreme specialisation and sensitivity to relative price changes.

The Armington assumption has implications for producers' and consumers' decisions. For firms, some of their intermediate inputs will be imported, and the choice over imported or domestic inputs will depend on their relative prices, as well as the Armington elasticity. For consumers, some goods will be a composite of imported and domestic inputs. Similarly for the consumer, the choice over imported and domestic goods will depend on relative prices and the Armington value.

3.1.1.7 Model closure

The number of endogenous variables for which the CGE model can obtain a solution is clearly constrained by the number of independent equations. Accordingly, this requires that a number of model variables are specified as exogenous, thereby determining the model closure. This choice reflects the (primarily macroeconomic) assumptions within which the policy analysis is set, and therefore depends on the nature of the issue being addressed.

Although a 'classic' CGE model yields a full-employment equilibrium with market clearing prices, many researchers impose alternative macroeconomic closures on the framework. These exemplify some necessarily ad hoc assumptions concerning the characteristics of agents or markets, so as to impose more realistic macroeconomic behaviour on the neoclassical framework. These features include, for example, wage and price rigidities, partial adjustment mechanisms and non-market clearing equilibrium outcomes.

In particular, various model closures are often used to represent different assumptions about the operation of the labour market. To represent an assumption of involuntary unemployment, for example, the researcher may set employment as endogenous and exogenously fix wages at an above-equilibrium rate. Alternatively, a full employment, perfectly flexible labour market assumption may be represented by a model closure that sets wages as endogenous with and employment as exogenous so as to reflect the fixed labour supply of the economy.

---

[19] Some models do incorporate monopolistically competitive features and increasing returns to scale, often in the manufacturing sector (e.g Brown, Deardorff and Stern, 2003; Francois, van Meijn and van Tongen, 2003). The notion is that some products are differentiated according to their individual features, rather than their country of origin.

This practice, of course, has significant implications for GCE simulation analysis, including modelling the employment impacts of policy changes. The issue of imposing non-equilibrium employment assumptions is part of a wider debate on the alternative notions of equilibrium in macro and general equilibrium models (discussed in Malinvaud, 1977), and some authors explicitly criticise the combination of macroeconomic and Walrasian elements that are found in a multitude of CGE models (see: Bell and Srinivasan, 1984; Srinivasan, 1982). A discussion of this topic is outside the remit of this research, but Rattso (1982) and Robinson (1991) provide a survey of the debate.

3.1.2 Operationalising the model

3.1.2.1 Benchmark data and parameterisation

Figure 1.2 summarises the various steps involved in parameterising, specifying and simulating a CGE model. The key first step towards operationalising a CGE model involves selecting a benchmark data set, typically a SAM. This describes the characteristics of an economy for a representative year, highlighting the linkages that exist between sectors and regions. The SAM incorporates a number of sources of information: the I-O table for the economy; national accounts data; government accounts; balance of payments data and trade data. The I-O table contains production sector data, including sectoral linkages in the economy, and the contribution made by the primary factors of production. The national accounts disaggregate demand into consumption, investment, governments spending and exports and imports. The trade accounts provide detail on the composition and destination of exports and imports, and government accounts provide information on public expenditures and revenues.

The structural data embedded in the SAM are used to ascribe actual values to some of the parameters of the functional forms in the model system, for example the relative size and import intensity of sectors. The exogenous parameters are then imposed, informed by available data and existing studies. These parameters characterise the behaviour of producers and consumers in the model, and describe the responsiveness of producers and consumers to changes in relative prices and income. They include, for example: the elasticities of substitution in value added, thus determining the substitutability of labour and capital inputs to production; the demand and income elasticities of households and consumers; and the Armington elasticities that describe the elasticity of substitution of domestic and imported composites. Other parameter values, such as migration function parameters, can be determined exogenously by drawing from existing literature.

Figure 1.2 Procedures for CGE model operation

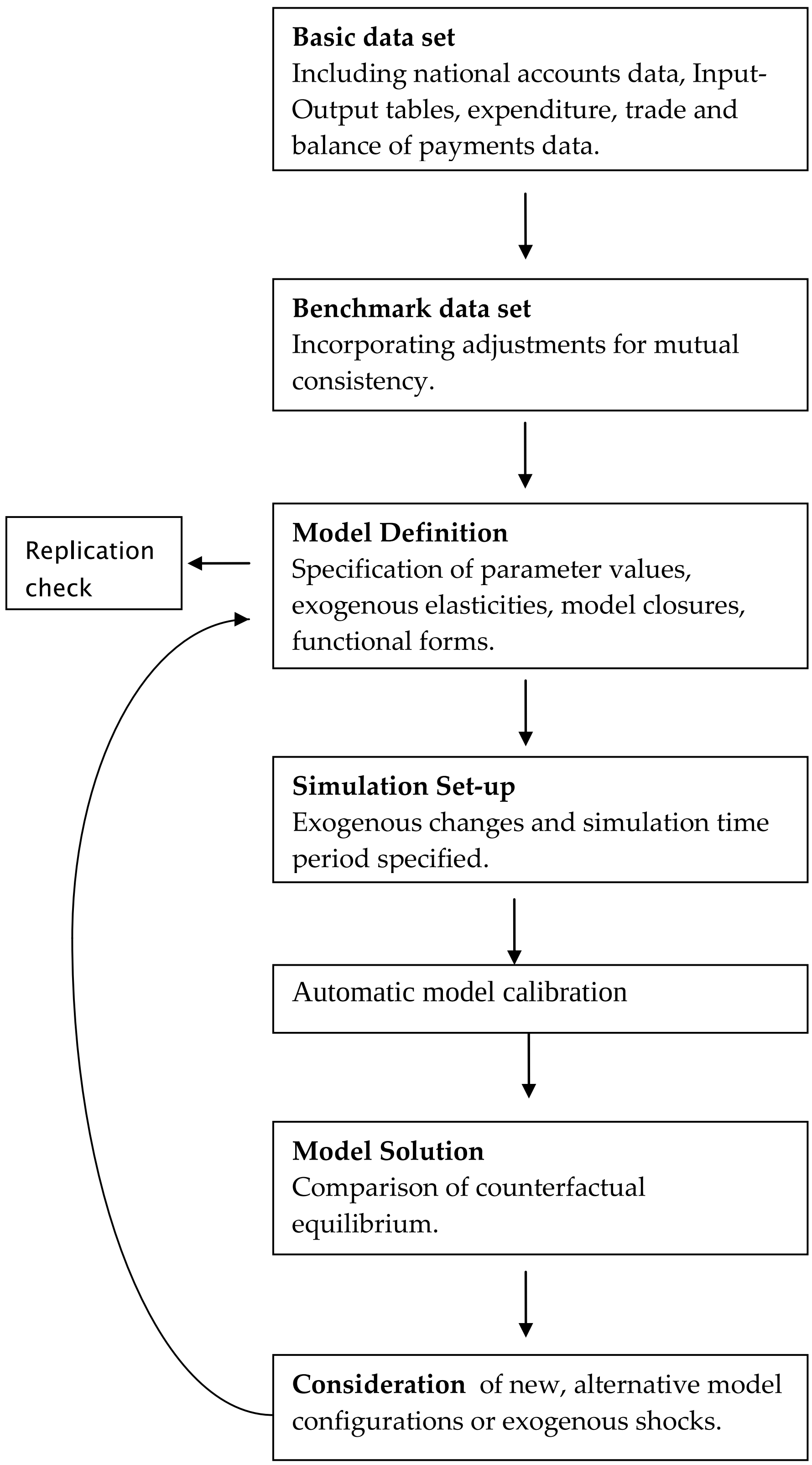


Figure 1.2 Source: adapted from Greenaway *et al* (1993), p.23.

3.1.2.2 Calibration

A final set of parameter values are determined through calibration of the model for the set of remaining unknown variables. This involves fitting the model to the benchmark data set: the remaining parameters are chosen and adjusted deterministically so that, together with the SAM data and the values of the behavioural parameters, the model is able to reproduce the benchmark data set.

3.1.2.3 Model simulation and equilibrium solution

Once the model is fully specified and parameterised, it can be used to simulate the effect of a policy shock or an exogenous change in economic conditions by specifying new values for policy instrument(s) or economic variable(s) of interest. The model is solved for a unique set of prices that identifies a new market equilibrium, where an equilibrium is characterised by the equalisation of demand and supply across all markets simultaneously. Different settings for the exogenous variables will produce different market equilibria, and it is therefore possible to evaluate the effects of alternative policy changes or economic shocks. Each policy change is associated with an equilibrium, allowing for direct comparison amongst policy alternatives.

The simulation outputs are used to analyse the effects of the exogenous change on the endogenous variables of the model – consumption, production, prices, exports, employment, and so forth, and/or the impact on welfare, depending on the model specification[20]. The simulation results illustrate what the economy would look like if the exogenous shock were to take place, and the difference between the simulated response of the model variables and the base year data represents the effect of the policy or exogenous change. Once model results have been obtained and evaluated, modellers can consider running new simulations with alternative model configurations (for example by making changes to represent alternative production structures in the economy; different substitutability between production inputs; different government budget constraints; or different labour market scenarios etc.) or alternative policy shocks, in order to evaluate the sensitivity of the results to key model assumptions, or to compare and rank the impacts of alternative policies.

---

[20] CGE models are also often used to measure the impact of policy changes or exogenous shocks on economic welfare, using Hicksian compensating or equivalent variations measures, for example. Compensating variation is an estimate of the amount of money a consumer would be willing to accept in order to be compensated for a change in some circumstance (such as a change in prices, availability of goods or services, landscape quality etc), such that their overall utility is unaffected. Equivalent variation measures the amount of money a consumer would be willing pay in order to avoid a change in some circumstance. Greenaway et al. (1993, p.24) summarises the steps involved in these calculations.

3.1.3 Some examples of CGE applications to energy efficiency and renewables

There are a number of alternative methods by which the economic (and other, e.g. environmental) impacts of renewables and energy efficiency have been considered in CGE models. Allan et al (2007) summarises 8 (eight) CGE applications for the system-wide impacts of energy efficiency improvements. This literature used models for regions and nations to evaluate the impacts of efficiency improvements on energy use, as empirical contributions to the debate on "rebound" (see Sorrell, 2007). This found that both rebound and backfire (increases in the use of energy following the increase in the efficiency of its use) were observed in these studies.

This report made three suggestions for future research. Firstly, that the usefulness of CGE modelling for considering the system-wide impacts of energy efficiency improvements meant that the lack of studies was "surprising". A number or recent studies have sought to continue to make contributions to this growing literature (for instance: Mizobuchi, 2008; Hanley *et al*, 2009; Turner, 2009; Wei, 2010; Turner and Hanley, 2011).

Second, the use of appropriate elasticities within the model – such as between energy and other inputs in production – requires that these be estimated for the region or nation in which they are used as much as possible. The third recommendation was that results in terms of rebound – critical for the effectiveness of energy efficiency improvements – be subjected to extensive sensitivity analysis. This should allow the important assumptions to be made transparent, and the importance of specific variables and parameters for the model results. This has been taken up with enthusiasm in a number of papers. While not explicitly modelling energy efficiency improvements, Lecca *et al* (2010) extent the AMOS modelling framework to show the importance for model results of where energy is introduced into the hierarchical production structure of a CGE model. Turner (2009), for instance, details the specific outcomes for the estimated rebound effect from combinations of elasticities of substitution and trade elasticities used in the CGE model of the UK.

For renewables, some papers have examined the system-wide impact of expenditures related to investments in renewables. For many regions and nations, it is argued that the scale of development in renewables projected in the near future is of a scale which may be thought of as a "mega-project", and that the expenditures during this project will have significant effects on the economy as a whole. Unlike using an IO model, a CGE model can shed light on the nature of the response of the supply-side of the economy to large demand-side expenditures, e.g. rising wage costs as labour and prices are bid up in the short-run due to constraints on supply. Examples of this include Allan *et al* (2008) and (Lu *et al*, 2010).

Other studies have introduced the specific renewables technologies into the CGE framework and examined the system-wide consequences of changes in the amount of production from these technologies, including how these interact (or compete) with non-renewable technologies. Such studies for biofuels, for instance, have been undertaken at the national level (for example, Steininger and Voraberger, 2003; Dixon *et al*, 2007; Perry, 2008; Arndt *et al*, 2009; Wianwiwiat and Asafu-Adjaye, 2011) or from a global perspective (for example, Reilly and Paltsev, 2007; Banse *et al*, 2008; Gurgel *et al*, 2008; Kretschemer *et al*, 2009) and for developed and developing countries (Lee, 2011).

As identified by Allan (2011) both IO/SAM and CGE approaches have been used to examine the potential economic and environmental impacts of biofuels developments, with global CGE applications a particularly popular methodology. There would appear to be one fundamental reasons for this: CGE models (as we have seen) characterise the structure of all markets, including all factors of production. Particularly for biofuels, which require agricultural land, for instance, changes in the demands for particular types of agricultural land will affect the rental prices of land, the amount of different types of agricultural products (including biofeedstock) produced and the uses of these agricultural products (including for exports). Not taking into account the system-wide impacts of these disturbances would not be representative of the range of impacts that biofuels could be expected to have. Particularly in this example, any possible changes to existing use of agricultural lands could drive the environmental gains which result from developing biofuels production.

3.2 Identification of different types and sub-types

3.2.1 Interregional and regional CGE models: 'top down' versus 'bottom up' approaches

Regional and interregional CGE models are designed to provide an understanding of the interactions within and amongst regions, and a quantitative representation of the spatial economic system. There are two approaches to constructing a regional or interregional CGE model: the 'top down' approach and the 'bottom up' approach. The choice between each model type usually reflects a trade-off between data requirements and theoretical sophistication[21]. The top-down method involves the use of national CGE model results, which are then disaggregated to a regional level on an ad hoc basis. The mapping of the economy-wide results to a regional dimension takes place without any feedback effects from the regions, and there is no explicit modelling of the behaviour of agents at the regional level. As such, the analysis of regional policies or regional economic shocks cannot be analysed within the framework. The reduced theoretical refinement of the model structure does, however, mean that they are relatively less data-demanding compared with the bottom-up approach.

In contrast, in a bottom up structure, regional agents' behaviour is explicitly modelled, and a fully interdependent system allows national-regional feedback effects to occur in both directions. In contrast to the top-down approach, national results are obtained from the

[21] See Liew (1984) for a discussion.

aggregation of regional results. The regional interlinkages can be modelled using regional estimates of trade (commodity flows) and factor mobility (in particular labour mobility). The data requirements are thus very demanding, and necessitate use of an interregional I-O database, interregional trade elasticities and other variables, for which regional econometric estimates are not often available. However, this type of structure can be used for analysing the effects of disturbances that originate in the regions, and are therefore better suited for detailed regional policy evaluation.

In interregional models, the degree of interaction between regional markets can differ across models. Factor mobility plays an important role in determining the extent and characteristics of interregional relationships. Factors can be allowed to move across sectors and regions. Labour supply has received most focus from researchers, with labour migration motivated usually by wage differentials. Capital is normally assumed to be immobile between regions in the short-run and, where permitted, long-run capital movements tend to be driven by sectoral and/or regional differentials on rates of return or productivity.

Another important aspect of a regional or interregional CGE model is the macroeconomic closure of the system. For single region models, the small-economy assumption usually holds (i.e. the modelled economy is too small to affect other economies interest rates or incomes). Interest rates and exchange rates are exogenously determined in the wider national economy. Extra-regional prices are exogenous, whilst regional prices are usually endogenous. Interregional models relax the assumption that the prices of other regions' outputs are exogenous. For an interregional model, regional prices and quantities are determined endogenously within the system, though the role of interest and exchange rates needs to be defined.

The development of regional and interregional CGE models has been slower than that of national models, most likely due to the data constraints involved in model specification. Nevertheless, there are a number of operational regional and interregional models in the literature and, as for the literature on national CGE modelling, the studies differ widely in terms of model structure, type of application, country of origin and so forth. A large proportion of regional and interregional CGE models relate to the Australian and the US economies, and they are most commonly used for analysis of price-based policies, such as taxes and subsidies.

Examples of some early interregional CGE models include the multi-regional variant of the ORANI model (Dixon et al., 1982). This model provides a top-down approach in addressing regional issues. Other similar top-down interregional models include Horridge et al. (1995), and more recently Parmenter and Welsh (2000) combined a top-down regional equation system with the MONASH dynamic model of Australia (Dixon et al., 2000) to produce the MONASH-RES model for use in regional forecasting and policy analysis[22].

Hybrid approaches (e.g. Higgs *et al*, 1988; Liew, 1995) are essentially top down, but incorporate some limited elements of the bottom-up approach which allows for more explicit specification of the regional economies. Higgs et al. (1988) present a top-down equation system that incorporates a partially regionalised CGE model. The national data set is sectorally disaggregated such that regional sectors are explicitly specified. This allows for analysis of some regional shocks, but the absence of feedback effects between the regions rules out analysis of region-wide shocks. Liew (1995) does incorporate some feedback effects between the regions, but the source of the interaction is limited to only one component of final demand.

For analysis of policies originating in a regional context, a bottom-up model is the most appropriate modelling methodology, since this allows for endogenised interactions amongst the regions via interregional linkages which are crucial to the outcome of the policy-related shocks. McGregor *et al* (1996a) compare the results of the single region AMOS CGE model for the Scottish economy with the interregional AMOSRUK version, where interregional behaviour is explicitly modelled, and find that exogeneity assumptions regarding regional prices and quantities can generate significant long-run bias in the results for regional variables. Parmenter *et al* (1985) compares the simulation results of a national policy shock using three basic CGE frameworks which are constructed according to the bottom-up, top-down and hybrid approaches. The author uses a specially constructed illustrative database to minimise data bias, and he too finds significant differences in the results for each of the model types.

(i) Interregional linkages and closure rules

Interregional linkages in a CGE model typically arise via trade commodity flows as well as via factor mobility of capital and labour. The nature and extent of such interregional feedback effects has been shown to have a significant effect on results (see Section 4.2.1 above). In a series of simulations using an interregional CGE model for Indonesia, which incorporates interregional trade and factor mobility, Watanuki (1996) shows that new investments in less developed regions lead to relatively greater benefits for more developed regions via interregional feedback effects.

Factor mobility also has an important role in depicting interregional linkages. Interregional, intersectoral and/or international factor mobility may be incorporated. Capital is generally assumed to be immobile in the short-run, and those studies that allow for long-run capital mobility tend to motivate long-run capital movements via differences in rates of return or productivity amongst regions and sectors. The determination of investment is also important.

[22] More recent interregional versions of the MONASH model adopt a bottom-up specification (Gieseike and Madden, 2006). These are discussed later in this section.

Labour mobility is commonly stimulated by regional wage differentials. Harrigan and McGregor (1988) demonstrate that differences in the configuration of the UK labour market relating to the mobility of labour (as well as wage determination) can have an important impact on simulation results. Morgan et al. (1989) incorporate varying degrees of labour mobility, from perfect mobility through to immobility, and also find that the extent of labour mobility has a significant impact on regional growth, because constraints on the supply of labour mean that less capital is drawn to the region.

Mechanisms other than wage differentials have also been used to motivate interregional labour mobility. In Ko (1985) and Ko and Hewings (1986), labour mobility depends on wage differences across sectors and regions, as well as differentials in expected wages over some horizon plan, in the spirit of the Harris-Todaro (1970) hypothesis. Jones and Whalley (1988, 1989) assume partially mobile labour among regions by establishing that individuals' migration decisions are based on a trade-off between income differentials amongst regions and their locational preference. Thus Jones and Whalley (various years) assume that individuals in each region hold different degrees of locational preference, and the authors specify individuals' utility function in a region as being the maximisation of two sub-utility functions; each of which represent the utility derived from consuming the same basket of goods inside and outside the region. Gazel (1994) incorporates the utility-equalisation across space theory used in urban economics, whereby labour migration depends on wage and price differentials, up to a limit when utility is equalized in all regions.

The closure specified for the model heavily reflects the theoretical or policy application of the model and, for interregional models, plays a role in determining the nature of the interlinkages between the individual regions. For example, the range of labour market specifications available in the AMOSRUK model for the UK represent alternative visions of the regional macro-economy. These labour market closures reflect different assumptions about wage determination and population constraints. By changing these assumptions, the nature, direction and extent of regional interactions are affected.

In Peter et al. (1996), for example, the authors consider the determination of regional investment via alternative closures within the multi-regional MONASH-MRF model: comparative statics and forecasts. In the former, capital stocks in regional sectors are exogenously specified. Aggregate investment is also determined exogenously, and is allocated across the regional sectors according to relative rates of return. This configuration is used to show the effects of one or a few exogenous changes to variables of interest. For the forecasting simulations, the demand for investment in each regional sector is described by an estimated forecast growth rate for the industry capital stock and an accumulation relation which links the capital stock and investment rate of the forecast year to that of the following year/period. In contrast to the comparative static set-up, the forecast specification also incorporates changes in all exogenous variables that are assumed to occur during the simulation period. This requires that estimates are drawn from other sources, such as government or private sector macro forecasts.

(ii) Calibration

The calibration method employed in CGE models has been reviewed by a number of authors (see, for example, Shoven and Whalley (1992), Koh et al. (1993) and Partridge and Rickman (1998)). The sometimes limited availability and reliability of regional and national data present various calibration and data-related problems for CGE models, which can lead to bias in the result estimates. Many CGE models are calibrated on input-output tables which are constructed via industry survey techniques to estimate commodity flows. Where national or regional commodity flows data are not available (or only partially complete), some authors use non-survey techniques to estimate these variables. Non-survey techniques involve the use of ad-hoc judgement, reliance on other indicators, or data-smoothing adjustments in order to construct data flows which are thought to represent actual data flows and to satisfy certain known constraints or characteristics in production and trade. Gravity-type models are one such non-survey technique for estimating commodity flows (see, for example, Leontief and Strout, 1963; Gibson et al., 2004). This method involves predicting trade flows between two countries or regions based on the economic size of the market in each country (based on GDP or industrial production) and their geographic proximity.

To estimate regional trade relationships in the absence of I-O tables, Hulu and Hewings (1993) perform improvised separations of the rows and columns of a national I-O table on the basis of both (i) extraneous regional industry shares and (ii) the relative sizes of the supplying and purchasing sector and the relative size of the region. In the MONASH-MRF model, which is a bottom-up regional CGE model (in the sense that behavioural relationships are specified at the regional level), the construction of the interregional I-O table involves spatial disaggregation of the national table via ad hoc splits of rows and columns based purely on regional shares. Haddad and Hewings (2003) argue that this could compromise the modelling process, and that the hybrid techniqueHulu and Hewings (1993) (where national I-O tables are regionally disaggregated based on both industrial shares and relative industry/region sizes) is more theoretically sound. Using this hybrid procedure, Gazel (1994) estimates interregional trade data, and carries out sensitivity analysis for the interregional commodity flows data. A 10% increase in imports was found to have no impact for aggregate income results, though there were substantial differences for capital and labour incomes. Moreover, even where fully specified interregional I-O tables are available, there may be issues regarding the construction method. Israilevich et al. (1996) reveals that differently constructed I-O tables would have a significant effect on the results of a regional econometric model, both in forecast and impact analyses.

3.2.2 Dynamic CGE frameworks

Advances in computing software, together with the appeal of CGE modelling as a tool for policy analysis, has meant that CGE modelling has been a productive area of research in recent years. Until relatively recently, CGE models, especially regional and interregional models, tended to be comparative static in nature. An important area of progress in CGE modelling relates to the incorporation of dynamic properties into the model structure (Harrison et al., 2000), allowing for growth to be endogenised. In most cases, the dynamic properties are recursive in nature. This involves the linking of a sequence of single-period equilibria through stock-flow relationships. The computed equilibria vary over time as the value for the model's stock variables adjust. Flows in previous time periods (for example investment, interregional migration, and government borrowings) have an effect on values of endogenous variables computed in each period via their influence on the values for the stock variables in each period (for example capital, population and government debt). Recent examples of this type of dynamics exist in the RAEM 3.0 model (Ivanova, 2007), a CGE model for the Netherlands. This framework incorporates dynamics of capital accumulation and technological progress, stock and flow relationships and backward looking expectations. In each period, the model is solved for an equilibrium given the exogenous conditions assumed for that particular period, with the equilibria linked via capital accumulation.

In contrast, full multi-period dynamic CGE models explicitly incorporate agents' forward looking expectations, and this requires all periods to be solved simultaneously. There are few of this type of CGE framework in the literature, though Bröcker and Korzhenevych (2008) specify one such model, which endogenises the savings-investment behaviour of forward-looking agents. In this model, households are assumed to maximise their utility function over time, taking into account their intertemporal budget constraints, and that prices and interest rates vary over time. For their part, firms maximise their present values, and the existence of capital stock adjustment costs smoothes the response of capital stocks to shocks.

Dynamic specifications in regional and interregional models have been much slower to develop. The AMOSRUK model incorporates recursive dynamic aspects relating to endogenous investment and interregional migration, though recent developments have included a fully dynamic specification, where agents' forward looking expectations are accounted for (see Lecca et al. (2011) for an energy-related application) . Similarly, in the multi-regional Australian MONASH model, recursive dynamics are incorporated as before: flows of investment, migration and/or government borrowing in preceding time periods determine the values for endogenous variables computed in each period via their contribution to the model's stock variables in each period (such as capital, population, government debt) (Dixon and Rimmer, 2002).

By endogenising potentially important sources of economic growth, these models may capture crucial aspects of a policy change or exogenous shock that a static simulation excludes, and therefore over- or under-state the benefits from a policy-induced exogenous shock. Despite this particular shortcoming of comparative static models, a large number of simulations are of this kind, owing to the fact that dynamic models, being more theoretically complex, are more difficult to solve.

3.2.3 'Hybrid' CGE frameworks

There are also a number of empirical dynamic macroeconomic models which are linked with national CGE models via variables that are endogenous in one and exogenous in the other, so that the results of the macro models are imposed on the CGE model[23]. Whilst some authors advocate the robustness of this so-called 'ecumenical' modelling strategy, others prefer a direct fusion of the two techniques, whereby a CGE model is embedded in a dynamic macro model, allowing for Walrasian CGE elements to be integrated with macro or financial models. Robinson (2003) and Robinson and Lofgren (2005) provide a discussion.

3.2.4 Overlapping Generation CGE models

Other dynamic CGE models include the overlapping generation (OLG) type, which are based on the early developments of Auerbach and Kotlikoff (1987). In these models, there is a turnover of population: individuals live for two periods and at any point in time, there are two generations ('old' and 'young') living together. When a policy influences two generations in different ways (e.g. a tax reform that benefits one generation more than the other), there will likely be consequences for the aggregate savings rate, capital accumulation and economic activity. The OLG CGE model allows such important intergenerational issues to be considered. Recent applications include that of Wendner (2001), who considers the possibility of using revenues from CO_2 taxation to partially finance the pensions system, and shows that environmental policy and pension reform may be mutually compatible objectives. Although OLG CGE models have also proved useful in the analysis of other policy concerns, such as social security reform and ageing and demographic issues, in practice, an OLG CGE framework with multiple regions and sectors still presents a considerable computational difficulties, and requires several trade-offs with the level of detail that can be captured by the model.

3.2.5 Imperfectly competitive CGE models

Other recent CGE models explicitly incorporate imperfect competition. Since the seminal work of Harris (1984), which incorporates imperfect market features such as market power and price setting, there have been a range of modifications made to the standard CGE model in order to introduce imperfectly competitive elements. Many approaches assume that products are heterogeneous across firms and countries/regions, and that firms possess a degree of market power, though there are key differences in assumptions regarding price discrimination, product differentiation, strategic behavior, expectations and market entry. Extra data are required to calibrate the model and, where these data are not completely available, as is often the case, additional ad hoc assumptions may be imposed. These technical choices in the design of the

---

[23] Powell (1981) describes an early application of this approach using the ORANI model of Australia.

model structure may have an important impact on model results, and may increase uncertainty regarding model outputs.

Roson (2006) compares results from the same simulation exercise (the removal of trade tariffs and subsidies for agricultural goods in the EU, which implies a drop in agricultural prices in the EU and an increase in rest of world agricultural prices) across alternative configurations. The configurations include one standard competitive and three distinct imperfectly competitive model configurations (with alternative assumptions on the presence of economies of scale and free market entry, for example) The author finds that the simulation leads to an improvement in competitiveness in the EU manufacturing industry, and that the existence or not of imperfect competition does affect the simulation results and policy implications. For example, the impact of the positive policy shock (on overall production activity) is stronger under imperfect competition than under perfect competition (because producers' marginal costs are lower for firms with market power), so that the existence of market power acts as a "boost" to policy impacts. Furthermore, under perfect competition the domestic economy (the EU) is the region benefiting the most from the overall welfare gains relative to the rest of the world, thereby possibly justifying the policy of trade liberalization from an EU perspective. However, under some imperfectly competitive scenarios, the domestic region's overall welfare is unaffected, whilst some foreign regions experience most of the gains, as a result of changes in the terms of trade between countries. Thus the distribution of the policy gains is affected by the type and existence of market power, which would likely lead to different policy decisions.

3.3 Data requirements and availability for OECD and UK

Being empirical models, CGE models are particularly data-intensive. Structural parameters will be required, and might be taken, for instance, from an IO table or SAM for the economy under consideration. Additional data relating to the parameterization of various behavioural functions will also be required. The data requirements are therefore larger than those for IO models. Normally behavioural parameters are not estimated with regression analysis as in econometric models, but are either deduced from a single year's data, or specified exogenously using estimates from literature.

Numerous CGE frameworks exist for OECD countries. The ORANI CGE model of Australia (Dixon et al., 1982) has been used extensively for policy analysis. Adaptations of the model exist for many countries including North America, though no ORANI model exists for the UK. Like the classic CGE models, it is derived from orthodox micro assumptions about the behaviour of price-taking agents. In the base model, there are 113 domestic industries, 115 commodities and 9 labour occupations. Various 'add-on' facilities allow the model to be adapted to suit the policy purpose (for example, extending the labour categories to up to 72 occupations or regionalising the model to the level of 6 Australian states[24]). Market clearing

---

[24] See Section 3.2.1 for more discussion of the interregional model variant.

equates demand and supply for domestically produced commodities, though non-equilibrium notions, such as unemployment, can be accommodated. The modeller can define, for example, the conditions of the balance of trade, and alternative wage-setting scenarios and time horizons of analysis. An additional CGE framework which is part of the ORANI line of models is MONASH (Peter et al., 1996). This is a 113-sector CGE model of Australia with extensions that allow the incorporation of up to 282 occupations and numerous types of households, and which has also been applied to other countries. Most aspects of MONASH correspond to, or are very minor developments of, the theory underlying the ORANI model described above (Dixon et. al., 1982)[25], though the treatment of capital accumulation and investment introduces some dynamic interactions into the framework that are absent in ORANI.

The AMOS[26] suite of CGE model frameworks (see Harrigan et al.,1991 and McGregor et al., 1996a), have been used extensively for UK economic analysis on a variety of issues, including national and regional policy analyses. The model structure is a flexible one, and a range of model closures corresponding to different time periods of analysis and labour market options is available. Energy-economy-environment studies include, for example, an analysis of the impact of increased efficiency on the industrial use of energy (Allan et al. 2007); the concurrent and legacy effects of establishing a marine energy industry in Scotland (Allan et al. 2008); the potential for rebound and disinvestment effects on oil consumption in response to an increase in energy efficiency in the transport sector in Scotland (Anson & Turner, 2009); and the impact of demand disturbances on the UK interregional environmental 'trade balance' (Turner et al. 2009). Other recent AMOS-variant studies which incorporate estimates of employment effects resulting from non-energy regional policies or economic disturbances include analyses of: the national impacts of UK regional policy (Gilmartin et al. 2007); the macroeconomic impact of demographic change in Scotland (Lisenkova et al. 2007); the importance of graduates to the Scottish economy; the impact of fiscal policy expansion in Scotland (Lecca et al 2010). The basic AMOS model structure has also been calibrated with other-country SAM databases for applications relating to Sardinia (Lecca, 2009); Ethiopia (Gela, 2000); and Greece (Pappas, 2008).

The parameterisation of CGE models continues to be a contentious issue (see Section 3.4 on the strengths and weaknesses of CGE modelling), particularly for regional and interregional models, where data constraints are significant. Behavioural parameter estimates for CGE models are often taken from external literature, even though they are often for different countries/time period/level of disaggregation. A number of authors have contributed to advancements in this area. Partridge and Rickman (1998) suggest practical solutions that lie somewhere in-between model calibration and full econometric estimation of CGE models. For example they highlight that Adams and Higgs (1990) compute averages of a number of years of data for a key sector

---

[25] All aspects of the MONASH model are described in Dixon and Rimmer (1997).

[26] A macro-micro model of Scotland.

due to concerns that the benchmark data set may not be representative of the underlying economic structure. Other approaches include that of Adkins et al. (2003), who use a Bayesian approach to estimate production function parameters in a regional CGE model of Oklahoma, where regional data was limited and of poor quality. The Bayesian approach involves taking into account prior information about likely values of the elasticities or other parameters. Since the abundance and quality of data is greater at a national than a regional level, estimates based on these can be a good source of prior information for Bayesian estimation at the regional level. Alternatively, in a CGE model of Mozambique, Arndt et al. (2002) use a maximum entropy approach to calibrate the model, and use the framework to explain Mozambique's recent history.

For CGE modelling in the UK, there have been a number of important developments in recent years. The dynamic AMOS version by Lecca et al. (2011) which incorporates forward-looking agents as well as behaviour aspects, including habit formation, (see Section 3.2.2) is the first of its kind in the UK, and also the first attempt to incorporate an explicitly disaggregated renewable energy sectors within the production sector, which represents a significant step forward. Although data availability constrains some of the Bayesian method improvements described above, there is a growing UK research community focused on various CGE modelling developments and parameter estimation in the energy-economy-environment area, including projects funded by the EPSRC.

3.4 Strengths and weaknesses of CGE modelling

3.4.1 Strengths of CGE modelling

A key strength of the CGE modelling approach relates to its microfoundations. In CGE models, the optimizing assumptions associated with general equilibrium modelling are typically preserved, which therefore allows for an analysis of the effects of a policy or exogenous change at the micro level. The method involves explicitly modelling the behaviour of producers and consumers, so that behavioral assumptions are clearly stated, and this formal structure aids in the comprehension and transparency of the model. Despite the incorporation of these complex microfounded relationships, CGE models are still able to produce a numerically precise equilibrium solution to the model simulations.

Alongside the benefits of having credible theoretical underpinnings, the model structure allows that alternative model specifications can be compared and contrasted, allowing for a full examination of the effects of different functional forms on the model simulation results (Cox and Harris, 1985; Greenaway et al., 1993). Further, CGE is particularly useful when examining the impact of novel policies or new sectors, to which econometric methods would not be applicable.

The ability to incorporate interdependencies and feedback effects is another important feature of the CGE approach. The regional impact of changes in policies or exogenous shocks may be significantly different from the aggregate effects (Nijkamp et al., 1986, pp.259 and 261; Miller and Blair, 1985, p.63). Furthermore, most policy changes are likely to have impacts on employment and other economic measures beyond only the target variable or sector. Such economy-wide, spatially-disaggregated effects are difficult to capture in anything other than a general equilibrium framework. The complexity and multitude of the interlinkages mean that an assessment of a policy shock or reform could not be carried out analytically in sufficient detail. Only computer based-simulations allow for all the interactions to be incorporated and tracked. A CGE model therefore offers significant value in understanding these complex interactions in the economy, and the corresponding employment impacts.

The degree of aggregation of the model will be dependent upon the policy question at hand, but a further useful aspect of the CGE framework is that, should a sector or subsector be of particular interest, it is relatively straightforward to disaggregate the data set upon which the model is based[27]. This means that the analyst can identify and compute the gains and losses on employment (or other economic variable) of the policy at the sub-sectoral level for the sector of interest. In addition, not only can the model identify the sources of income gains or losses from the policy reform, but it can also show how these effects are distributed among sectors or regions or employment groups (or groups of society or social class of household, depending on the data used to specify the model). Since all policy effects will have distributional consequences across the economy - whether sectoral, spatial or welfare-related - this feature helps inform policy assessment[28].

The flexibility inherent in a CGE framework makes it particularly useful for evaluating the response of the economy to a range of policy shocks. Alternative types of model simulations can be carried out within a common framework using the same benchmark data set. Re-estimation of the framework is not required for each simulation, which aids the process of comparison, and the alternative deviations from that equilibrium can be considered for a range of exogenous shocks. Multiple simulations can be undertaken, for example, to work out alternative policy changes that might turn an aggregate or sectoral employment loss into a gain, and the policy shocks can be either marginal or non-marginal in nature. The effects of policy 'packages' on employment, where there is a change to more than one exogenous variable, can also be considered and compared. Alternatively, where there is uncertainty surrounding some aspect of the economy, such as the true characteristics of the operation of regional labour markets, for example, various configurations can be incorporated into the framework, and the consequences for model results on employment and the wider economy

[27] However, this is subject to data availability and, in the case of interregional models in particular, a degree of aggregation is often required in order to ensure data consistency.
[28] In principle the CGE construct can model welfare changes explicitly through the use of measures such as compensating variation and equivalent variation, so as to consider the net welfare benefits of alternative policy reforms within a framework with solid theoretical foundations.

can be analysed. Similarly, alternative parameter values can be incorporated into model simulations in order to check for robustness of results. The existence of a common framework within which alternative model simulations are conducted means that each set of results can be numerically ranked in terms of the impact on employment (or the distribution of employment across sectors, or some other policy measure such as aggregate income or welfare), according to the specific policy issue.

An additional attribute of the CGE approach to modelling is that it disciplines thinking about the structure and operation of actual economies, which is a crucial prerequisite for sound policy-making. CGE models can validate or refute policy-makers' presentiments about the likely effects of a policy, and can emphasise unanticipated outcomes. They help to demonstrate the means via which a policy works its way through the economy and, for the case of period-by-period analyses, explicitly describe the adjustment process of the economy and corresponding employment impacts. As they do so, the model results can highlight any anomalies in the short-run versus the long-run effects. Further, they encourage a more inclusive approach to policy analysis by helping to develop a wider perspective about the impacts of a policy or exogenous shock on employment and the economy as a whole.

Finally, CGE modelling lends itself particularly well to informing policy formulation at the regional level. Regional time series data sets are often inconsistent or insufficient in terms of the number of observations for regional econometric modelling approaches, which often come up against significant constraints in their specification and implementation. As a result, assessment of regional policy has often involved the use of purely demand-side models based on I-O frameworks (Armstrong and Taylor, 2000, p.35). Although the data requirements of such methods are relatively low, there are significant limitations to the approach (see Section 2.4). CGE models, on the other hand, are able to overcome some of these limitations without the requirements of rich data sets (although there are issues relating to the reliance on secondary sources for the parameterisation of key model variables, and the timeliness and consistency of official I-O tables, as discussed in Section 2.3).

3.4.2 Weaknesses of CGE modelling

As with all techniques in applied economics there are limitations associated with the CGE methodology, though modellers can adopt a number of approaches that attempt to minimise these.

Although, theoretically, a CGE model can accommodate any functional form, modellers typically use only 'well-behaved' functional forms that are relatively straightforward and tractable to use. This often means CES or Cobb-Douglas forms, for example, being specified in the model. Whilst there is a significant volume of literature to suggest that CES functional forms fit production and consumption data relatively well and perform well in such econometric studies (see Arrow et al., 1961; McFadden, 1963; Uzawa, 1962), in practice, agents' behaviour may not actually be consistent with these. Furthermore, the results of a number of studies stress that

CGE model predictions may be sensitive to the use of the CES class of functions versus, for example, flexible functional forms (Hertel, 1985; McKitrick, 1998).

Similarly, modellers face various constraints relating to the numerical specification of the model. The model is calibrated to a benchmark year, which is assumed to be in equilibrium, and the calibration practice is justified on the grounds that the values which result from the calibration process are consistent with the equilibrium. However, the assumption of an equilibrium may not necessarily hold in practice (see further discussion later in this section), and there are no procedures for checking the validity of the calibrated values. Furthermore, this benchmark data set is often aggregated to a degree that can obscure important underlying relationships (including sectoral employment effects). This aggregation may be necessary for interregional CGE analyses in particular, where national or regional I-O tables need to be aggregated to ensure consistency. An additional important criticism of the CGE approach is the quality of the information used to derive the parameters which are not specified using the SAM data or via calibration. For example, Hertel et al. (2004) accept that the history of estimating the substitution elasticities governing trade flows in CGE models has been "checkered" at best. In many cases, CGE model builders do not statistically estimate these parameters themselves, but use estimates from secondary sources, and these often do not relate to the same time period or geographical location of the analysis. The substitution and Armington elasticities of the GTAP multi-country CGE modelling framework (Hertel, 1999b; Dimaranan et al., 1999), for example, are taken from the SALTER project (Jomini et al., 1991), and are mapped to the appropriate GTAP sectoral classification. The income elasticities are taken from the Food and Agriculture Organisation's (FAO) World Food Model (FAO, 1993), which itself uses some variable estimates drawn from secondary sources (Theil et al., 1989). The secondary data estimates often relate to different country and/or commodity coverage than that of the original model (e.g. Hertel, 1999b).

Moreover, there is no capacity for formally testing the appropriateness of functional forms, parameter values or model structures. Unlike for macroeconometric models or partial equilibrium econometrically estimated models, there is no means of applying diagnostic tests, comparing actual versus fitted values, or measuring the degree of confidence that the user can have in the model results. However, formal sensitivity analysis can be used to examine the robustness of CGE model results, and focused sensitivity analysis for parameter values and behavioural functions is a useful means of testing the significance of particular assumptions in influencing model outcomes. Roberts and Phimister (2012) carry out "systematic sensitivity analysis" to indicate the robustness of their results to changes in all trade and production elasticities within their model.

The existence of data constraints often necessitates the use of secondary data sources for parameter values. However, one way of alleviating this criticism would be for the modeller to provide additional information in the form of, for example, standard errors, functional form, and so forth relating to the estimates, since this could provide some information about the reliability of such estimates. In practice, space constraints in academic articles often prohibit this, though references are often (but not always) provided. Systematic validation of CGE simulations, through sensitivity analyses of the parameter values and/or model specification, as well as ex post validations of the results, is therefore beneficial for supporting the credibility of model results.

The perceived uniqueness of particular solution values is also a potential weakness of CGE analysis. The modeling approach assumes a unique equilibrium exists, and results are computed on this basis. In practice, however, multiple equilibria are possible. The use of the 'well-behaved' functional forms of, for example, the CES type makes this an unlikely prospect, however. There are no known cases of multiple equilibria, and the convention in the literature is to assume that a unique equilibrium exists unless shown otherwise (Greenaway et al., 1993).

A further weakness is related to the specification of the model structure: specifically to the difficulty involved in incorporating important economic phenomena into the model framework. In particular, the incorporation of intertemporal flows, expectations, growth processes in general, monetary sectors and monetary flows is not straightforward in CGE modelling.

Although other modelling methods, such as dynamic stochastic general equilibrium (DSGE) and macroeconometric models, are more advanced in their treatment of dynamics, this feature can create its own modelling constraints relative to the CGE approach. The added complexity of a dynamic model framework, for example, can render the modelling method more assumption driven, and less tractable that static models, and the increased data requirements can make this a difficult (and in some cases possibly unnecessary) approach for many policy analyses[29]. On the other hand, simple, static simulations are likely to miss crucial parts of the story. In some regards, since information about an economy and the way that it will react to changes is never perfect, the modeller may be able to lessen reservations about precise model results and reduce the possibility of reliance on spurious results by obtaining a range of possible estimates based on alternative parameter assumptions and model specifications, and including intertemporal variants where feasible.

Overall, although CGE techniques provide invaluable guidance for policy-making and enable analysts to consider the consequence of policy changes on employment, the simplifying assumptions that are often necessarily imposed, together with various data constraints, mean that the outcomes of CGE models must often be interpreted as 'insights' rather than absolute truths. Criticisms have been made of CGE applications when the authors assert a degree of precision over the results, which perhaps cannot be justified by the quality of information that is inputted to the model, or the extent of sensitivity of the results to assumptions.

---

[29] Though intertemporal calibrated CGE models do exist – Lecca et al. (2009) presents such a model for the region of Sardinia.

In the presence of these constraints, there are a number of ways to encourage greater confidence in the simulation results. These include sensitivity analysis: changing the model parameters or model specification in order to determine the effect on the simulation results. In the case of parameter sensitivity analysis, Piermartini and Teh (2005) suggest that if a subset of parameters of the model has been estimated econometrically, then information on the standard errors of the estimated parameters can be used to inform the sensitivity analysis[30].

Furthermore, Kehoe (2003) has suggested the practice of systematic ex post evaluations of CGE simulations. This involves the CGE modeller comparing the results of the CGE model with actual data, in order to see if the results can be validated by outcomes, or whether comparisons with actual data throw up surprises that warrant further investigation. Kehoe (2003) follows this process to consider the performance of CGE predictions of the impact of NAFTA. This type of *ex post* evaluation is routine for macroeconometric forecasting models. While there may be a need for conducting more *ex post* validation of CGE models and simulations, it should be noted that this is not a trivial task. In a standard comparative static analysis for a model calibrated for, say the year 2000, the model is shocked by changing one or more exogenous variables, such as imposing a domestic demand shock, and the results of the simulation are compared with the base year for 2000. An *ex post* validation of the simulation would involve comparing these results with actual data in, say, 2005. However, for the sake of consistency in comparison, the process would involve removing all extraneous effects that occurred in the intervening years, such as the impact of significant regional, national or global economic events.

Perhaps the most often stated criticism of CGE modelling is the so called 'black box' nature of the simulations. This refers to the conjecture that the causality between assumptions underlying a CGE and the results produced often remain impossible to decipher, due to the complexities of the relationships that are modelled (Hertel, 1999a). This therefore lessens confidence in the results and the robustness of the outputs. This is perhaps an issue relating to poor explanation of the structure and results of the models rather than the model itself. However, to the extent that modeling is responsible for this criticism, a number of simple routines can address this issue. Extensive sensitivity analysis (which might be “systematic”, e.g. Roberts and Phimister (2012), or more targeted at a few key parameters) and an incremental approach to model augmentation can help to reveal the exact causalities underlying the adjustment process that follows from an exogenous shock. Furthermore, the transparency of CGE model structures and closures, together with a flexible model framework which allows the modeller to track the source of any surprising results, also aids the clarity of interpretation of

---

[30] That is to say, the parameter values could be drawn ‘randomly’ from a population that has the same probability distribution as those from the econometric estimation (Piermartini and Teh, 2005, p.20). See Roberts and Phimister (2012) for an application of “systematic sensitivity analysis” to all production and trade elasticities within their CGE model.

the results. John Whalley, a pioneer in CGE modelling, acknowledges that CGE models are not intended as forecasting tools constructed to give an accurate picture of the future time path of actual economies, but are instead a form of theory with numbers which generates insights rather than precise forecasts (Whalley 1986, p.3).

4. Macroeconometric models

4.1 Exposition of nature and operation of method

Macroeconometric models encompass a wide range of probability models for macroeconomic time series analysis and estimation and inference procedures. The models are used to address multitude different issues, including examining the impacts of policy measures; understanding propagation of policy shocks; or examining the determinants of business cycle fluctuations or economic growth.

Whilst macroeconometric methodologies are prevalent in the current literature for some types of macroeconomic studies (notably monetary policy analysis), their complex solution techniques and significant time-series data requirements mean that their application to renewable energy-related issues is very limited. Thus our analysis and overview of the usefulness of this methodology is necessarily shorter and more limited than that of the I-O and CGE methodologies. However, there are a few energy-related applications using macroeconometric modelling methods which could be relevant to renewable-energy policy appraisal in the presence of more complete data series, which makes this a potential growth area for research for the future. We include examples of these in our discussion.

Owing to the wide variation in the nature of the macroeconometric methods popular today, in the preceding section we identify and describe the operation of those individual methodologies which are prevalent in the current literature or in policy analysis.

4.2 Identification of different types and sub-types

Popular modern macroeconometric models which are currently used for policy analysis include dynamic stochastic general equilibrium (DSGE) models. Early DSGE models were developed to study how real shocks to the economy might cause business cycle fluctuations (Kydland and Prescott, 1982). The models incorporate rational, infinite-lived, identical households who maximise intra- and inter-temporal utility. They are closely related to CGE models in terms of specification and computation: they are founded on microeconomic assumptions about tastes, technology, constrained optimisation and general equilibrium, and have often relied on calibration rather than estimation for parameterisation. In contrast to CGE models, however, agent maximisation occurs within a stochastic (i.e. randomly-determined) environment, rather than a deterministic one (i.e. a process which is “pre-determined”; whereby the result is entirely determined by initial states). One advantage of the stochasticity of the model is that it lends itself to econometric estimation and the fitting of time series data. Recent DSGE models have become more complex, with increased structural shocks, real and monetary frictions and adaptive expectations being considered within the framework for added realism and improved empirical fit to the data.

Dynamic optimization and optimal control theory models also have their uses in policy analysis: they are able to trace the dynamics of the economy over time, and aid the selection of the optimal time path of policy changes according to specified criteria. Macro-based models of this type, however, are generally not capable of modelling distributional effects, whereas micro-based models in this category tend to rely on partial equilibrium principles, precluding their ability to model the economy-wide interlinkages and feedback effects that are the stronghold of CGE models. These models have in common the problems of data adequacy, parameterization and model specification that CGE models face. The dynamic complexity of the model structures often require reliance on exogenously specified parameters, and the same issues arise relating to the influence of the modellers judgement, expertise and biases on model specification, as for CGE modelling. No doubt owing to their large data requirements and complex solution methods of optimal control and DSGE models, we do not see any examples in the literature of these models being used to estimate the impacts on employment or the economy of renewable policy support mechanisms.

Although not strictly macroeconometric models, vector autoregression (VAR) models have been used to econometrically estimate the relationships between the energy market (including renewable energy) and the macro economy. VAR models are statistical models used to identify whether there are interdependencies between multiple time series and, where relationships do exist, to measure their extent. In doing so, they describe the evolution of a set of variables over a sample period. VAR models are not necessarily macroeconometric, since they do not explicitly model all parts of the economy. However, we briefly mention here a few relevant examples of VAR analyses which consider the relationships between renewable energy consumption and key macroeconomic variables. For example Apergis and Payne (2012) find a relationship between renewable and non-renewable energy consumption and economic growth and the labour market (with this relationship having bi-directional causality). Menegaki (2011), in contrast, finds no causal relationship between renewable energy consumption and economic growth, but does confirm a relationship between renewable energy consumption and employment effects. Both these analyses require rich data sources (for example the latter analysis uses data on renewable energy consumption, economic growth and employment across 27 countries and with 10 years of observations). The literature on energy consumption and economic growth has been extensively examined in the literature (see Ozturk 2011 for a review), whereas studies on renewable energy consumption have only recently been investigated, highlighting the potential for new analysis on this sector as data become available.

A different type of macroeconometric framework used for analyslying the economic impacts of renewable energy policy-making is the MDM_E3 model (and its variants), developed and used exclusively by the consultancy firm Cambridge Econometrics. This model is distinct from the purely econometric models described above. Cambridge Econometrics describes the framework as macroeconometric, but strictly speaking, the model is an amalgamated I-O one. The I-O framework is based on a set of input-output coefficients which are updated with econometric time series relationships. Embedded within the main model is a series of sub-models (energy, electricity supply and environmental emissions sub-models). These sub-models update specific prices and demands, which then feed back into the main model and are used to update the IO data. Operation of the model requires a large number of exogenous assumptions concerning the future energy and economic environment. These exogenous assumptions relate to macroeconomic conditions over time (including forecasts of: the economic growth rate, diesel petrol and gas prices, fuel duties, domestic and trading partners' inflation rates, exchange rates, interest rates, domestic tax rates, government expenditures and government policies, for example).

In Cambridge Econometrics (2010), the authors forecast the economic and environmental effects of "green fiscal reform" (GFR): a change in the taxation burden away from labour or firms and towards pollution and the use of natural resources. The authors forecast a large number of scenarios, including low, medium and high fuel prices, alternative specifications of the tax shift, and the ringfencing or not of tax revenues for spending on environmental goods and services (such as subsidies for wind farms, hybrid vehicles and home insulation). The model is run for the alternative scenarios (also incorporating all the exogenous assumptions about changes in macroeconomic conditions over time, for example, which update the I-O data in each period), and consider the resultant impacts on the economy (including employment effects), energy demand, and pollution emissions.

The authors use this model framework to explicitly forecast (rather than simulate on a comparative static basis) the impact of the policy change. The authors forecast that the type of green fiscal reform they consider would lead to employment increases across all sectors during the forecast period (to 2020), and a reduction in pollution emissions. The employment gains are attributed to the fact that the tax burden is shifted away from labour and towards pollution and natural resources. The authors suggest this then reduces firms' labour costs (via lower national insurance costs, for example) and thus increases the demand for labour.

Although this model framework (and its variants) have been used for a number of applications in a consultancy context, the specific MDM model versions, and the theoretical concept on which they are based (i.e. an I-O framework which is updated via econometrically-estimated relationships and forecast variables), has not been tested or critiqued (or indeed made widely available) in the academic literature. The model equations are not publically available, so it is difficult to reconcile the numerical results with intuitive understanding or established theory, in some cases. For example, in the case of the Cambridge Econometrics (2010) report, the authors forecast an increase in employment across all sectors as a result of the fiscal reforms, which is accompanied by no change (or a small reduction) in GDP. Intuitively, we might expect the fiscal reforms to lead to a fall in price competitiveness for the UK for energy-intensive production compared to other countries (assuming the reforms are UK-based only), which may be offset by the reduced labour costs. It is difficult to reconcile this negative impact with a boost to employment in all sectors without more detail about the model structure, elasticities of substitution between production inputs, and the underlying data and assumptions etc. While the analysis is indicative, the results are, of course, heavily dependent upon these specific assumptions made, as well as the multitude forecast data incorporated into the framework, although the sensitivity analysis is a recognition of this.

4.3 Data requirements and availability for OECD and UK

Macroeconometric models are the predominant methodology in the literature for analysing monetary policy and other financial and macroeconomic issues. The relatively high data frequency of financial, exchange rate and macroeconomic indicators mean that there are sufficient observations to perform sophisticated statistical analyses and econometric estimations at the country level.

Macroeconomic data for key macroeconomic indicators (such as GDP, exchange rates, inflation, interest rates etc) are available in long time series and for many indicators at high frequency for the UK and OECD countries (for example from the OECD statistics database; and Bloombergs for high-frequency financial data). For employment data, timeseries are available at the country, regional and sectoral level from OECD also (though at lower frequency compared to some macroeconomic data).

In the case of specific industries, however, greater data constraints exist. For general energy market data series, there are high frequency data on carbon prices, energy consumptions (including renewable energy consumption), energy prices from various sources, including the International Energy Agency database and the World Bank Development Indicators. Accordingly, there are a number of macroeconometric studies focused on the macroeconomic effects of policy at a highly aggregated level (e.g. the impact of monetary policy decision-making on GDP and employment) and, in the wider energy field, on the relationship between energy prices or energy consumption and GDP. For highly disaggregated analyses, such as the impact of specific renewable policy measures on employment, however, there are significant data constraints. This is reflected in the lack of macroeconometric analyses of this type. It is likely that, as the renewable energy industry becomes more established over time, data collected on activity in this industry will allow greater macroeconometric analysis of the relationships between activity in this sector and employment and GDP performance.

4.4 Strengths and weaknesses of macroeconometric modelling

In some regards, CGE modelling can be seen as complementary to macroeconometric models, in the sense that some of the weaknesses of the CGE approach are the strengths of these other approaches and vice versa. Macroeconometric models are able to explain the impact of a change in economic policy on aggregate variables in an economy over time. They have a firm basis in economic theory, and, unlike many CGE models, they are typically adept at incorporating detailed dynamic characteristics of the economy such as expectations, growth, capital accumulation and resource depletion. In addition, they are able to embrace notions of market disequilibrium, and monetary variables, for which CGE models are also typically less advanced in their treatment[31]. Furthermore, the parameterization methods of macroeconometric models are superior to those of CGE models, since the modeller can use time series data and well-understood estimation techniques. This is in comparison to the reliance on calibration, and exogenous determination for many key parameters within a CGE model. Significantly, the econometric estimation of the models means that there are the associated benefits of diagnostic testing in the form of calculation of standard errors, confidence intervals and so forth, which is also lacking in the CGE approach.

Nevertheless, macroeconometric models often have insufficient detail of the microeconomic structure of the economy. The production, investment and consumption functions that macroeconometric models are based on may not be a satisfactory reflection of the microeconomic structure of the economy. Furthermore, macroeconometric models tend to be lacking in their ability to provide sufficient detail on the distributional and efficiency effects of exogenous changes, which can pose limitations in terms of estimating sectoral employment impacts following precise policy changes, for example. These two limitations of macroeconometric models are accepted as strengths of CGE modelling. Even though CGE functional forms may be regarded as rather straightforward, and parameterization techniques could be improved upon, the approach is consistent with microeconomic theory, and permits a differential treatment of sectors. This last issue is of particular relevance to the analyses of employment effects from policy support for energy efficiency and renewable technologies, for example, because of the importance of identifying detailed sectoral impacts.

Macroeconometric modelling, like CGE modelling, is also constrained with regards to the adequacy and availability of data, and for macroeconometric modelling, particular concerns relate to the time consistency of the data being used and the ability to model structural shifts over time. In fact, one of the key advantages of macroeconometric modelling – the ability to reliably estimate parameter values from time series data – constrains its use for the purpose of the analyzing the employment effects of energy policy support, since insufficient time series data exist, particularly at the regional level, but also at the national level, to be able to fully estimate a sufficiently-detailed multi-sectoral macroeconometric model of the UK economy.

Lastly, macroeconometric modelling faces the same reliance on the modeller's judgement over the choice of the structural specification of the model, functional forms and so forth. Whereas in CGE modelling there may be biases in terms of the modeller's choice of production

[31] Though attempts have been made to include dynamic characteristics and imperfect competition in CGE models (see Section 4.3).

technology, closure rule and source of exogenously determined parameters, the judgement and expertise of a macroeconometric modeller will be reflected in their choice of model structure amongst, for example, Keynesian, monetarist or an ad hoc alternatives, or in the treatment of expectations or the incorporation of time varying parameters. However, a macroeconometric modeller can test the appropriateness of some model specifications, such as functional forms, subject to adequate data requirements, whilst a CGE modeller must often rely on other work to justify their choices.

There have been significant advancements in procedures to formally econometrically parameterise DSGE models (see Canova, 2007). However, the complexity of DSGE models means that they are difficult to solve and analyse. Accordingly, they tend to abstract from sectoral and regional detail and incorporate fewer variables, making them less useful for the type of policy analysis of job creation impacts of energy policy, for example. They are more appropriate for examining the dynamics of the aggregate economy, and have been used extensively for monetary policy analysis (Clarida et al., 1991). Although the DSGE methodology has yet to be used for regional policy analysis[32], Rickman (2009) suggests that the techniques for estimation and dynamic fitting of DSGE models provide important insights for the future research direction of CGE analysis.

5. Employment impacts and uncertainty

5.1 Employment impacts

5.1.1 IO

As noted above, conventional "demand-driven" IO analysis considers three forms of effect arising from a demand disturbance: "direct", "indirect" and "induced" effects respectively. As an example, we can consider the impact of the creation of 10 new jobs in one sector of the economy. We assume that this sector has a Type 1 employment-employment multiplier of 1.3 and a Type 2 employment-employment multiplier of 1.5.

The direct employment effect is the impact on employment in the individual sector in which the new jobs are created. This is therefore 10 jobs. The Type 1 effect includes the direct effect and the indirect effect and is calculated by multiplying the Direct effect by the Type 1 employment-employment multiplier. The total number of (direct and indirect) jobs created across the economy by the new 10 jobs is 13 (10 x 1.3). The Indirect effect therefore is three jobs (13-10). The Type 2 employment effect includes the direct, indirect and induced effects and is calculated by multiplying the Direct effect by the Type 2 employment-employment multiplier. The total

[32] To our knowledge, at the time of writing, there exist no published regional DSGE models.

number of (direct, indirect and induced) jobs created across the economy by the 10 new jobs is 15 (10 x 1.5). The Induced effect therefore is 2 jobs (15-13). For this example, therefore, 10 new (direct) jobs create 3 further jobs through the "indirect" effect and 2 further jobs through the "induced" effect, making 15 jobs created in total.

As noted in Section 2 above, the difference between the direct, Type 1 and Type 2 multipliers for individual sectors will vary due to differences in the inputs required in production by each sector. Multipliers can be calculated for all variables of interest, which might include output, income, value added and employment, although we have focused on employment-employment multipliers in this example.

5.1.2 CGE

CGE modelling will capture the whole-economy effects of changes in the structure or demand or supply features of an economy. Given its flexibility, it has been argued that IO is a special case of CGE modelling in which specific assumptions about the nature of production functions (i.e. linearity) and labour markets (i.e. fixed real wage) are imposed. Such an approach is not however the typical way in which CGE models are calibrated for the useful point that these models are designed to deal with non-linearities and endogenous prices (formed from the equilibrium between supply and demand). Such models, for instance, can include constraints on the availability of factors of production. This might lead to crowding-out of activity (and employment) in some sectors as activity and employment in others is stimulated.

The way in which the labour market is modelled will be crucial for the extent of crowing out and the employment impact of the policy modelled. Further to this, although perhaps more important for regional than national modelling, is the adjustment process by which factor constraints are adjusted over time. Regional economies, for instance, could be expected to have no such constraints on labour supplies as migration flows could adjust. This may not typically be a characteristic of regional models, in which labour supplies are more typically assumed fixed. A result of this could be that modellers may wish to consider regions within a nation in an inter-regional framework, with migration possible between regions, but national labour supply being "exogenous". This would serve to illustrate the extent to which employment increases seen in specific regions with policy action might be wholly or partially offset by reductions in employment in non-stimulated regions.

5.1.3 Macroeconometric

Whilst modern macroeconometric models in theory provide a sophisticated methodology for analysing the employment impacts of renewable energy policy support, in practice the existing data do not allow for any meaningful analysis of this specific issue. In the presence of time series data on, for example, renewable and non-renewable energy policy expenditures and disaggregated sectoral industrial production and employment figures (perhaps along with comparative public expenditures, production activity, and employment in other sectors), more detailed analysis of the employment effects of specific policy spending could be carried out. Since there does not seem to be any evidence of this type of data series being collected at present, it may be the case that this specific type of analysis is not likely to be conducted for some time.

Nevertheless, the availability of energy-sector data (such carbon prices, energy prices etc), and the growing data availability of renewable energy sector indicators (such as renewable energy consumption, renewable energy export estimates etc.) does mean that there is research being done using macroeconometric models in the wider energy-environmental-economy field. With a better grasp of the relationships between macroeconomic activity and the energy and renewable energy industry, this is likely to have important contributions to policy making in a wider sense, including for considering employment effects.

We would agree with the conclusions of Berck and Hoffmann (2002, p. 154) that each of the modelling approaches outlined in this note "[have] its place in assessing the employment effects of environmental and natural resource policy". The most practical and useful modelling approach in practice will differ between the economic characteristics of the specific area, the type of policy disturbance being simulated and the specific requirements from the application. For instance, IO or SAM approaches can shed useful light on the way by which different sectors or income groups might be affected by specific changes, however this approach is silent on the extent to which the competitiveness of production for instance, would be affected.

5.2 Applicability of results to other regions/nations

Results from multi-sectoral analysis should be only be considered relevant for the specific region and scenario which is modelled in each case. The precise extent of impacts of renewables and energy efficiency on employment, for example, will critically depend on the structure of the economy being modelled and the sectors in that economy. The nature of the labour market will be critical as well. Sensitivity analysis in papers published so far, for example – even for the same disturbance in the same nation (Allan *et al*, 2007) – show that economic and environmental results can vary considerably with the structure of the labour market.

Recent papers in the energy efficiency literature, for instance, have attempted to quantify the factors determining the scale of the rebound effect using CGE models and thorough sensitivity analysis. These have shown that the size of the rebound effect is an empirical question, rather than a theoretical one, and that "rebound" is intimately tied with the general equilibrium elasticity of demand for energy in efficiency units (Hanley *et al*, 2006). From the quickly-growing CGE modelling literature, it is evident that results on rebound, for example, cannot be carried over from one region or nation to another. The extent of rebound from each energy efficiency intervention is likely to be an empirical issue, depending on a multitude of factors including (but not limited to) the characteristics of the target industry/sector, the energy intensity of the sector and the economy as a whole, and the openness of the economy to trade and migration. Good academic studies will identify and discuss the important factors behind the modelled results and the importance of these factors to results will be shown through sensitivity analysis. As discussed above, one of the particular strengths of CGE modelling is the ability to carry out systematic sensitivity analysis of this sort.

IO analysis, and, for instance sectoral multipliers, also relate exclusively to the regional or national IO table from which they have been calculated. Sensible analysts should not carry over a sectoral multiplier, say an employment-employment multiplier, from one jurisdiction to another to evaluate the knock-on effects of direct employment changes. This would be incorrect for a number of reasons. The multiplier captures the knock-on effects of demand disturbances within a particular area. This uses the nature of production within that region, both for the directly stimulated sector(s) and for other sectors to which the sector(s) is (are) linked through backward linkages. Moving from one jurisdiction to another we would not expect all linkages to remain constant. An important factor is the size of the region, for example, as larger regions will tend to have lower imports and so smaller leakages from the economy at each round of the multiplier. The "ripple effects" of the multiplier therefore, could be expected to be greater in a national economy. This will crucially also depend on the specific pattern of intermediate inputs to that sector.

5.3 Confidence and uncertainty

With regards to the accuracy of the results of the three modelling approaches outlined in this note, we make the following points.

Specifically for IO studies, the values of multipliers are obtained from the Leontief inverse matrix for the region or nation which is the focus of the IO table. The backward linkages given in the table, for instance, for the basis for multipliers, but could be subject to error in their estimation. Kop Jansen (1994, p. 56) argues that "the composition of [the Leontief inverse matrix] is not an easy task. Enormous amounts of data are to be collected, separated, divided over sectors and aggregated… It is therefore widely recognised that the obtained coefficients depend not only upon the original data, but to a large degree upon the way they are carried through each step of the [table] construction process as well". This could have consequences for the values of multipliers derived, which will be crucial when these multipliers are used for generating estimates of the knock-on impacts of demand changes.

To address this uncertainty, recent research has assumed that values of technical coefficients in IO tables (the values in the A matrix) are stochastic and to see how this affects the multiplier values which could be obtained (Kop Jansen, 1994). A wide number of applications have recently explored the empirical importance of uncertainty in IO analysis (notably the work of Beynon and Munday, 2007; 2008).

For CGE applications, we have noted above that these are commonly parameterised using estimates of elasticities from the literature or from "best guess" estimates where such parameters are not available for the region or nation which is the focus of analysis. Further, the behavioural assumptions of (for example) the labour market can be crucial for the results obtained from these models. In such cases, sensitivity analysis can reveal the importance of these variables for results obtained. This should be undertaken systematically changing individual parameters in turn, explaining the motivation for testing each parameter and revealing the importance of these for results. With this done, readers can understand the robustness of the reported result. Macroeconometric models are subject to some of the same constraints as CGE models, in particular that of the model structure reflecting the modellers' assumptions about how the economy works, and data constraints. Whereas sensitivity analysis is used by CGE modellers to examine the appropriateness of the model assumptions and parameter values, there is recourse to formal diagnostic testing for macroeconometric models.

References

Adams, P. D. and Higgs, P. J. (1990). Calibration of CGE models from synthetic benchmark equilibrium datasets. *Economic Record, 66*, 110–126.

Allan, G.J., Bryden, I., McGregor, P.G. Stallard, T., Swales, J.K., Turner, K.R. and Wallace, A.R. (2008). Concurrent and legacy impacts from establishing a marine energy sector in Scotland. *Energy Policy*, 36 (7), 2734–2753.

Allan, G.J., Gilmartin, M., McGregor, P., Swales, J.K. and Turner, K. (2007), "Computable general equilibrium modelling studies", Technical Report 4 for UKERC Review of Evidence for the Rebound Effect, Working Paper, October 2007.

Allan, G.J., Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2007). The impact of increased efficiency in the industrial use of energy: A computable general equilibrium analysis. *Energy Economics*, 29 (4), 779–798.

Allan, G.J., McDonald, J., McGregor, P. and Swales, J.K. (2008). A distinctive energy policy for Scotland?. *Fraser Economic Commentary*, 32 (1), June 2008, 62–72.

Allan, G.J. (2011). The regional economic impacts of biofuels: A review of multi-sectoral modelling techniques and evaluation of applications. Strathclyde Discussion Papers in Economics, No. 11-30.

Allan, G.J., Gilmartin, M., McGregor, P.G. and Swales, J.K. (2011a). Levelised costs of wave and tidal energy in the UK: Cost competitiveness and the importance of 'banded' Renewables Obligation Certificates. *Energy Policy*, 39, 23–39.

Allan, G.J., McGregor, P.G. and Swales, J.K. (2011b). The Importance of Revenue Sharing for the Local Economic Impacts of a Renewable Energy Project: A Social Accounting Matrix approach. *Regional Studies*, 45 (9), 1171–1186.

Anson, S. & Turner, K. (2009). Rebound and disinvestment effects in oil consumption and supply resulting from an increase in energy efficiency in the Scottish commercial transport sector. University of Strathclyde Discussion Papers in Economics No. 09-01.

Adkins, L. C., Rickman, D. S., & Hameed, A. (2003). Bayesian estimation of regional production for CGE modeling. *Journal of Regional Science*, *43*(4), 641–662.

Apergis, N. & Payne, J.E. (2012). Renewable and non-renewable energy consumption-growth nexus: Evidence from a panel error correction model. *Energy Economics, 34*, 733–738.

Armstrong, H., & Taylor, J. (2000). *Regional Economics and Policy*. Oxford: Blackwell Publishing.

Arndt, C., Robinson, S. & Tarp, F. (2002). Parameter estimation for a computable general equilibrium model: A maximum entropy approach. *Economic Modelling, 19,* 375-398.

Arrow, K. J., Chenery, H. B., Minkas, B. S., & Solow, R. M. (1961). Capital labor substitution and economic efficiency. *Review of Economics and Statistics, 63*, 225-50.

Auerbach, A. J., & Kotlikoff, L. J. (1987). *Dynamic fiscal policy*. Cambridge: Cambridge Univ. Press.

Batten, D. (1982). The international linkages between national and regional input-output models. *International Regional Science Review*, *7*(1), 53-68.

Bell, C. L. G., & Srinivasan T. N. (1984). On the uses and abuses of economy-wide models in development policy analysis. In M. Syrquin, L. Taylor & L.E. Westphal (Eds.). *Economic structure and performance* (pp. 451-476). New York: Academic Press.

Beynon, M.J. and Munday, M. (2007). An aggregated regional economic input-output analysis within a fuzzy environment. *Spatial Economic Analysis*, 2 (3), 281-296.

Beynon, M.J. and Munday, M. (2008). Stochastic key sector analysis: an application to a regional input-output framework. *Annals of Regional Science*, 42, 863-877.

Berck, P. and Hoffmann, S. (2002). Assessing the employment impacts of environmental and natural resource policy. *Environmental and Resource Economics*, 22, 133-156.

Blair, P.D. (1979), *Multiobjective regional energy planning*, Martinus Nijhoss, Boston, Massachusetts.

Blanco, M.I. and Rodrigues, G. (2009). Direct employment in the wind energy sector: An EU study. *Energy Policy*, 37 (8), 2847-2857.

Bröcker. J. & Korzhenevych, A. (2008). *Forward looking dynamics in spatial CGE models.* Paper presented at the European Regional Science Association congress 2008, Liverpool. Retrieved December 04, 2008, from *http://www.eefs.eu/conf/Prague/Papers/782_broecker_korzhenevych.pdf*

Brown, D. K., Deardorff, A. V. & Stern, R. M. (2003). Multilateral, regional and bilateral trade policy options for the United States and Japan. *The World Economy, 26*,6, 803-828.

Caldes, N., Varela, M., Santamaria, M. and Saez, R. (2009). Economic impact of solar thermal electricity deployment in Spain. *Energy Policy*, 37, 1628-1636.

Canova, F. (2007). *How much structure in empirical models?* (C.E.P.R. Discussion Papers, Number 6791).

Cambridge Econometrics (2010). *A Major Green Fiscal Reform for the UK: Results for the Economy, Employment and the Environment.* Consultancy paper prepared for the Green Fiscal Commission. Briefing paper No. 5. March 2010.

Carley, S., Lawrence, S., Brown, A., Noufashan, A. and Benami, E. (2011). Energy-based economic development. *Renewable and Sustainable Energy Reviews*, 15, 282-295.

Casler, S. and Hannon, B. (1989). Readjustment potentials in industrial energy efficiency and structure. *Journal of Environmental Economics and Management*, 17, 93-108.

Cox, D., & Harris, R. (1985). Trade liberalization and industrial organization: some estimates for Canada. *Journal of Political Economy, 93*(1), 115-45.

Dietzenbacher, E. (1997). In vindication of the Ghosh model: A reinterpretation as a price model. *Journal of Regional Science*, 37, 629-651.

Dimaranan, B. R., McDougall T., & Hertel, T. (1999). *Behavioural parameters.* In *GTAP 4 Data Base Documentation Centre for Global Trade Analysis* (unpublished manuscript). Retrieved January 12, 2007, from https://www.gtap.agecon.purdue.edu/resources/ download/ 289.pdf

Dixon, P. B., Parmenter, B. R., Sutton, J., & Vincent, D. P. (1982). *ORANI: A multisectoral model of the Australian economy.* Amsterdam: North-Holland Publishing Company.

Dixon, P. B., Parmenter, B. R., & Rimmer, M. T. (2000). Forecasting and policy analysis with a dynamic CGE model of Australia., In G. W. Harrison, S. E. Hougaard Jensen, L.

H. Pedersen and T. F. Rutherford (Eds.), *Using dynamic general equilibrium models for policy analysis* (pp. 363-405). Amsterdam: North Holland.

Dixon, P.B., Osborne, S. and Rimmer, M.T. (2007). The economy-wide effects in the United States of replacing crude petroleum with biomass. Paper presented at the 10th Annual Conference on Global Economic Analysis, Purdue University, USA, January 2007 draft.

Dixon, P. B., & Rimmer, M. T. (1997*). MONASH: a disaggregated, dynamic model of the Australian economy* (Centre of Policy Studies and Impact Project, Monash University, Melbourne).

Dixon, P. B. & Rimmer, M. T. (2002). *Dynamic general equilibrium modelling for forecasting and policy: a practical guide and documentation of MONASH.* Amsterdam: North-Holland.

Food and Agriculture Organization. (1993). *World Food Model – model specifications*. (Number ESC/M/93/1). Rome, Italy.

Francois, J., Van Meijl, H. & Van Tongeren, F. (2003). *Trade liberalization and developing countries under the Doha Round* (CEPR Discussion Paper, Number 4032).

Gazel, R. C. (1994). *Regional and interregional economic effects of the free trade agreement between the US and Canada*. Unpublished PhD thesis. Department of Economics, University of Illinois.

Gelan, A. (2000) Impacts of Devaluation on Urban-Rural Interactions: A Computable General Equilibrium Model for the Ethiopian Economy PhD Thesis, Department of Economics, Strathclyde University.

Ghosh, A. (1958). Input-Output approach to an allocation system. *Economica*, 25, 58-64.

Gibson, H., Anderson, J., & Riddington, G. (2004). *A comparison of national accounts, survey and location quotient based local area models and multipliers.* Paper presented at the EcoMod International Conference on input-output and General Equilibrium Data, Modelling and Policy Analysis, Brussels. Retrieved 21 October, 2009, from http://www.ecomod.net/conferences/iioa2004/iioa2004 _papers/riddington.pdf

Giesecke, J. A., & Madden, J. R. (2006). CGE evaluation of a university's effects on a regional economy: an integrated assessment of expenditure and knowledge Impacts. *RURDS*, *18*(3), 229-251.

Gilmartin. M., McGregor, P., & Swales, J.K. (2007). The national impact of regional policy: supply-side policy simulation with labour market constraints in a two-region Computable General Equilibrium model. University of Strathclyde Discussion Papers in Economics No. 07-05.

Gowdy, J.M. and Miller, J.L. (1991). An input-output approach to energy efficiency in the USA and Japan (1960-1980). *Energy*, 16, 897-902.

Greenaway, D., Leyborne, S., Reed, G., & Whalley, J. (1993). *Applied general equilibrium modelling: applications, limitations and future developments*. London, The Stationary Office.

Haddad, E. A., & Hewings, G. J. D. (2003)*. Interregional computable general equilibrium models: a survey on specification and implementation issues* (TD Nereus 05-2003, The University of São Paulo Regional and Urban Economics Lab, Sao Paolo).

Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2006). The impact of a stimulus to energy efficiency on the economy and the environment: A regional computable general equilibrium analysis. *Renewable Energy*, 31, 161-171.

Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2009). Do increases in energy efficiency improve environmental quality and sustainability?. *Ecological Economics*, 68 (3), 692-709.

Harrigan, F. & McGregor, P. G. (1988). "Price and quantity interaction in regional economic models: the importance of 'openness' and 'closures'". In F. Harrigan and P. G. McGregor (Eds.).

London Papers in Regional Science 19: recent advances in regional economic modeling. London: Pion.

Harrigan, F., McGregor, P. G., Perman, R., Swales, K. & Yin, Y. P. (1991). AMOS: A macro-micro model of Scotland. *Economic Modelling, 8,* 424-479.

Harris, R. (1984). Applied general equilibrium analysis of small open economies with scale economies and imperfect competition. *American Economic Review, 74(5),* 1016-1032.

Harris, J. R., & Todaro, M. D. (1970). Migration, unemployment and development: a two sector analysis. *American Economic Review*, *60*, 126-142.

Harrison, G. W., Hougaard Jensen, S. E., Haagen Pedersen, L., & Rutherford, T. F. (2000). *Using dynamic general equilibrium models for policy analysis*. Amsterdam: North-Holland.

Hertel, T. W. (1999b). *GTAP 4 1999 data base documentation - introduction.* (Unpublished manuscript, Centre for Global Trade Analysis). Retrieved November 16, 2008, from https://www.gtap.agecon.purdue.edu/resources/ download/122.pdf.

Heptonstall, P. (2007), "A review of electricity unit cost estimates", Working Paper Updated May 2007, UK Energy Research Centre, available online at www.ukerc.ac.uk/support/tiki-download_file.php?fileId=220.

Herendeen R.A. and Plant, R.L. (1981), "Energy analysis of four geothermal technologies", *Energy*, Vol. 6,p. 73-82.

Higgs, P. J., Parmenter, B. R., & Rimmer, R. J. (1988). A hybrid top-down, bottom-up regional computable general equilibrium model. *International Regional Science Review, 11,* 317-328.

Hulu, E. & Hewings, G. J. D. (1993). The development and use of interregional input-output models for Indonesia under conditions of limited information. *Review of Urban and Regional Development Studies*, 5.

Israilevich, P., Hewings, G. J. D., Schindler, G. R. & Mahidhara, R. (1996). The choice of an input-output table embedded in regional econometric input-output models. *Papers in Regional Science*, 75(2), 103-119.

Ivanova, O. (2007). *On the development of the new version of the RAEM model for the Netherlands (RAEM 3.0).* Paper presented at the ERSA European Regional Science Association Congress 2007, Paris.

Jomini, P., Zeitsch, J. F., McDougall, R., Welsh, A., Brown, S., Hambley, J., & Kelly, J. (1991). *SALTER: A general equilibrium model of the world economy: Volume 1. model structure, data base, and parameters* (SALTER working paper). Australia: Industry Commission. Retrieved

October 06, 2009, form http://www.pc.gov.au/ic/research/models/saltermodel/workingpapervolume1

Just, J. (1974). Impacts of new energy technology using generalised input-output analysis. *Computers and Operations Research*, 1, 97-109.

Kehoe, T. J. (2003). *An evaluation of the performance of applied general equilibrium models of the impact of NAFTA*. (Federal Reserve Bank of Minneapolis Research Department Staff Report, 320).

Ko, S. (1985). *A regional computable general equilibrium model for Korea*. (Unpublished Ph.D. dissertation, Department of Economics, University of Illinois).

Ko, S. & Hewings, G. J. D. (1986). A regional computable general equilibrium model for Korea. *The Korean Journal of Regional Science*, *2*, 45-57.

Koh, Y., Schreiner, D., & Shin, H. (1993). Comparisons of regional fixed price and general equilibrium models. *Regional Science Perspectives, 23*(1), 33-80.

Kop Jansen, P.S.M. (1994). Analysis of multipliers in stochastic input-output models. *Regional Science and Urban Economics*, 24, 55-74.

Kulišić, B., Loizou, E., Rozakis, S. and Šegon, V. (2007). Impacts of biodiesel production on Croatian economy. *Energy Policy*, 35, 6036-6045.

Kydland, F., & Prescott, E. (1982). Time to build and aggregate fluctuations. *Econometrica, 50*, 1350-72.

Lecca, P., McGregor, P. & Swales, K. (2010). Balanced budget government spending in a small open regional economy. University of Strathclyde Discussion Papers in Economics No. 10-20.

Lecca, P., Swales, J.K. and Turner, K. (2010). An investigation of issues relating to where energy should enter the production function. Stirling Economics Discussion Paper 2010-18, December 2010.

Lecca, P., Swales, K., and Turner, K. (2011). Rebound Effects from Increased Efficiency in the Use of Energy by UK Households. University of Strathclyde Discussion Paper in Economics No. 11-23.

Lee, D.H. (2011). Algal biodiesel economy and competition among biofuels. *Bioresource Technology*, 102, 43-49.

Lehr, U., Nitsch, J., Kratzat, M., Lutz, C. and Edler, D. (2008). Renewable energy and employment in Germany. *Energy Policy*, 36 (1), 108-117.

Leontief, W.W. (1941), *Structure of the American Economy, 1919-1929*, Harvard University Press, Cambridge

Leontief, W. & Strout, A. (1963). Multiregional input-output analysis. In T. Barna (Ed), *Structural interdependence and economic development*, (pp. 119-149). London: Macmillan.

Liew, L. H. (1984). "Tops-down" versus "bottoms-up" approaches to regional modeling. *Journal of Policy Modeling, 6,* 351-367.

Liew, L. H. (1995). *Modelling inter-regional strategic interactions within a general equilibrium framework* (In 1995 IFAC/IFIP/IFOR/SEDC Symposium on Modelling and Control in National and Regional Economies, Volume 2).

Lisenkova, K., McGregor, P., Pappas, N., Swales, K., Turner, K. & Wright, R. (2007). The macroeconomic impacts of demographic change in Scotland. University of Strathclyde Discussion Papers in Economics No 07-01.

Low, S.A. and Isserman, A.M. (2009). Ethanol and the rural economy: Industry trends, location factors, economic impacts and risks. *Economic Development Quarterly*, 23 (1), 71-88.

Lu, C., Zhang, X. and He, J. (2010). A CGE analysis to study the impacts of energy investment on economic growth and carbon dioxide emission: A case study of Shaanxi Province in Western China. *Energy*, 35, 4319-4327

Malinvaud, E. (1977). *The theory of unemployment reconsidered.* Oxford: Basil Blackwell.

McFadden, D. (1963). Constant elasticity of substitution production functions. *Review of Economic Studies, 30,* 73- 83.

McGregor, P. G., Swales, J. K., & Yin, Y. P. (1996a). *AMOS-RUK: An interregional computable general equilibrium model of Scotland and the Rest of the UK* (Paper presented at the 5th World Congress of the Regional Science Association, Tokyo, May 1996).

McGregor, P.G., Swales, J.K. and Yin, Y.P. (1996b). A long-run interpretation of regional input-output analysis. *Journal of Regional Science*, 36, 479-501.

Menegaki, A.N. (2011). Growth and renewable energy in Europe: A random effect model with evidence for neutrality hypothesis. *Energy Economics,* 33*,* 257-263

Miller, R.E. and Blair, P.D. (2009), *Input-output analysis* (2nd Edition), Cambridge University Press, Cambridge.

Morgan, W., Mutti, J. & Partridge, M. (1989). A regional general equilibrium model of the United States: tax effects on factor movements and regional production. *The Review of Economics and Statistics*, *71*, 626-635.

Nijkamp, P., Rietveld, P., & Snickars, F. (1986). Regional and multiregional economic models: a survey. In P. Nijkamp (Ed.), *Handbook of regional and urban economics.* New York: North-Holland.

Oosterhaven, J. (1980), *Interregional input-output analysis and Dutch regional policy problems*, Gower, Aldershot, UK.

Oosterhaven, J. (1988). On the plausibility of the supply-driven input-output model. *Journal of Regional Science*, 28, 203-271.

Oosterhaven, J. (1989). The supply-driven input-output model: A new interpretation but still implausible. *Journal of Regional Science*, 29, 459-465.

Ozturk, I. (2010). A literature survey on energy-growth nexus. *Energy Policy 38*, 340-349.

Pappas, N. (2008). Can migrants save Greece from ageing? A computable general equilibrium approach using G-AMOS. University of Strathclyde Discussion Paper in Economics 08-01.

Parmenter, B. R., Pearson, K. R., & Jagielski, R. (1985). *Bottoms-up, tops-down and hybrid methods for regionalizing computable general equilibrium models: some comparisons* (Centre of Policy Studies/IMPACT Centre preliminary Working Paper OP-52, Monash University).

Partridge, M., & Rickman, D. (1998). Regional computable general equilibrium modelling: a survey and critical appraisal. *International Regional Science Review*, *21*, 205-248.

Perry, M. (2008). Food production vs. biomass export vs. land-use change: a CGE analysis for Argentina (Unpublished paper, Munich Personal RePEc Archive Centre for Environmental Policy, Imperial College, London). Retrieved from http://mpra.ub.uni-muenchen.de/13442/

Peter, M. W., Horridge, M., Meagher, G. A., Naqvi, F., & Parmenter, B. R. (1996). *The theoretical structure of MONASH-MRF* (Centre of Policy Studies/IMPACT Centre Working Paper OP-85, Monash University).

Piermartini R., & Teh, R. (2005). *Demystifying modeling methods for trade policy* (WTO Discussion Papers No 10). World Trade Organization, Geneva, Switzerland.

Rattso, J. (1982). Different macroclosures of the original Johansen model and their impact on policy evaluation. *Journal of Policy Modeling*, *4,* 85-97.

Roberts, D. and Phimister, E. (2012). The role of ownership in determining the rural economic benefits of on-shore wind farms. *Journal of Agricultural Economics*, 63 (2), 331-360.

Robinson, S. (1991). Macroeconomics, financial variables, and computable general equilibrium models. *World Development, 19,* 1509-1525.

Robinson, S. (2003). Macro models and multipliers: Leontief, Stone, Keynes, and CGE models. In A. De Janvry & R. Kanbur (Eds), *Poverty, inequality and development: essays in honor of Erik Thorbecke*. Economic Studies in Inequality, Social Exclusion and Well-Being series. U.S: Springer.

Robinson, S., & Lofgren, H. (2005). Macro models and poverty analysis: theoretical tensions and empirical practice. Development Policy Review, *23*(3), 267-283.

Roson, R. (2006). Introducing imperfect competition in CGE models: technical aspects and implications, with an illustration about trade liberalization in agriculture. *Computational Economics, 28*, 29-49.

Round, J. I. (1978). An interregional input-output approach to the evaluation of nonsurvey methods. *Journal of Regional Science*, *18*(2), 179-194.

Round, J. I. (1983). Nonsurvey techniques: a critical review of the theory and the evidence. *International Regional Science Review*, *8*(3), 189-212.

Shoven, J. B., & Whalley, J. (1992). *Applying general equilibrium.* Cambridge: Cambridge University Press.

Sorrell, S. (2007). The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. A report produced by the Sussex Energy Group for the Technology and Policy Assessment function of the UK Energy Research Centre, October 2007.

Srinivasan, T.N. (1982). General equilibrium theory, project evaluation and economic development. In M. Gersovitz, & W. A. Lewis (Eds). *The theory and experience of economic development: essays in honor of Sir W. Arthur Lewis* (pp. 229-251). London: George Allen & Unwin, Ltd.

Steininger, K.W. and Voraberger, H. (2003). Exploiting the medium term biomass energy potentials in Austria. *Environmental and Resource Economics*, 24, 359-377.

Sue Wing, I. (2008). The synthesis of bottom-up and top-down approaches to climate policy modelling: Electric power technology in a social accounting framework. *Energy Economics*, 30, 547-573.

Swenson, D. (2006). Input-Outrageous: The Economic Impact of Modern Biofuels Production. Iowa State University paper, June 2006.

Swenson, D. and Eathington, L. (2006). Determining the regional economic values of ethanol production in Iowa considering different levels of local investment. Iowa State University paper, July 2006.

Theil, H., Chung, C. F., & Seale Jr., J. L. (1989). International evidence on consumption patterns. *Advances in Econometrics*, supplement 1. Greenwich, CT: JAI Press.

Turner, K. (2009). Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. *Energy Economics*, 31 (5), 648-666.

Turner. K., Gilmartin, M., McGregor, P. and J.K. Swales. (2009). The added value from adopting a CGE approach to analyse changes in environmental trade balances. University of Strathclyde Discussion Paper in Economics 09-03

Uzawa, H. (1962). Production functions with constant elasticity of substitution. *Review of Economic Studies, 29,* 291-299.

Walras, L. (1926). *Elements d'economique politique pure*. Edition definitive, translated by: Jaffe, W. (1954), *Elements of pure economics or the theory of social wealth*. London: George Allen and Unwin Ltd.

Wendner, R. (2001). An applied dynamic general equilibrium model of environmental tax reforms and pension policy. *Journal of Policy Modeling, 23*, 25-50.

Whalley, J. (1986) What have we learned from general equilibrium tax models? Working Paper 8625C, University of Ontario.

Wianwiwat, S. and Asafu-Adjaye, J. (2011). Modelling the promotion of biomass use: A case study of Thailand. *Energy*, 36, 1735-1748.

Verso Economics (2011). Worth the candle? The economic impact of renewable energy policy in Scotland and the UK. Report published March 2011.

Yamano, N. and Ahmad, N. (2006), The OECD Input-Output database: 2006 edition, STI Working Paper 2006/8, published 20th October 2006

Table 1: IO table for Scotland in 2007, 3 sector aggregation, £millions except where stated.

£million, 2007	Primary and manufacturing	Utilities and construction	Services	Total intermediate demand		Household	Government	Investment and stocks	Exports	Total final demand		Gross outputs
Primary and manufacturing	8080	2473	3162	13715		4061	1	1282	25726	31069		44785
Utilities and construction	1572	8050	2460	12081		2297	0	9663	3959	15919		28000
Services	4829	2332	28851	36011		35770	28747	2908	25853	93278		129289
Total intermediate inputs	14480	12855	34473	61808		42127	28748	13852	55538	140266		202074
Imports	13751	4776	18103	36630		21611	0	6311	1193	29115		65745
Net taxes on products and production	236	376	4584	5197		7541	0	1186	118	8845		14042
Compensation of employees	10220	5256	46432	61907		0	0	0	0	0		61907
Other value added	6097	4737	25697	36532		0	0	0	0	0		36532
Total primary inputs	30304	15145	94816	140266		29153	0	7496	1311	37961		178227
Gross inputs	44785	28000	129289	202074		71280	28748	21349	56850	178227		380301
Employment (FTE)	263,533	149,567	1,618,834	0								

Appendix A: IO modelling and estimation of multipliers

A.1 Input-Output modelling and multipliers

The structure of a regional economy can be described in a set of equations, and corresponds to reading along the rows of the IO table. These show how output for each sector (x_i) is produced for consumption by other industries (z_{ij}) and by elements of final demand for each sectors output (f_i). The first subscript shows the producing (row) sector, while the second shows the consuming sector. We describe the specifics of IO matrices using a three sector example (i.e. i, j = 3).

$$
\begin{aligned}
x_1 &= z_{11} + z_{12} + z_{13} + f_1 \\
x_2 &= z_{21} + z_{22} + z_{23} + f_2 \\
x_3 &= z_{31} + z_{32} + z_{33} + f_3
\end{aligned}
$$

Equation A1

We can represent the pattern of purchases made by each sector (i.e. reading down the columns for sector j) by calculating technical coefficients (a_{ij}) where:

$$a_{ij} = z_{ij} / x_j$$

Equation A2

We can restate Equation A1, replacing the z_{ij} elements with those from Equation A2. This gives us the following relationship between sectoral output and inter-industry purchases and sales to final demand.

$$
\begin{aligned}
x_1 &= a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + f_1 \\
x_2 &= a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + f_2 \\
x_3 &= a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + f_3
\end{aligned}
$$

Equation A3

If we express Equation A3 as the levels of inter-industry transactions and sectoral outputs in terms of the final demands for those sectors' output, we get:

$$
\begin{aligned}
x_1 - a_{11}x_1 - a_{12}x_2 - a_{13}x_3 &= f_1 \\
x_2 - a_{21}x_1 - a_{22}x_2 - a_{23}x_3 &= f_2 \\
x_3 - a_{31}x_1 - a_{32}x_2 - a_{33}x_3 &= f_3
\end{aligned}
$$

Equation A4

or

$$(1-a_{11})x_1 - a_{12}x_2 - a_{13}x_3 = f_1$$
$$-a_{21}x_1 - (1-a_{22})x_2 - a_{23}x_3 = f_2$$
$$-a_{31}x_1 - a_{32}x_2 - (1-a_{33})x_3 = f_3$$

Equation A5

In matrix notation, we can express equation 5 as:

$$(I - A)X = F$$

Equation A6

where capital letters denote we are considering matrices of each variable (F in this example is a 3 x 1 column vector, while (I–A) and X represent two 3 x 3 matrices. Rearranging Equation A6, we derive sectoral output in terms of the final demands for sectoral output and the inverse of the (I–A) matrix. This is the key equation in IO modelling, and the $(I–A)^{-1}$ element is termed the Leontief inverse matrix.

$$X = (I - A)^{-1} F$$

Equation A7

Equation A7 shows how (under the demand-side perspective) we can attribute output (X) to final demand (F) for the output of a regional economy. Identifying each of the individual elements of the F matrix – households, government, exports, etc. – we can estimate the importance of each category for regional output.

Alternatively, we can use Equation A8 to show the impact of changes in final demand on regional output.

$$\Delta X = (I - A)^{-1} \Delta F$$

Equation A8

The IO modelling described here is termed "open", in that all regional sectors are endogenous, while all categories of final demand are exogenous. Miller and Blair (2009, p. 34) argue, "in the case of households… the exogenous categorization is something of a strain on basic economic theory". Household income would increase when production expands, and households typically spend their earnings in "well patterned" ways (Miller and Blair, 2009, p. 35). Household spending therefore would be related to the level of economic activity in the region, so changes in regional activity would be expected to change the level of household spending.

A common IO practice is to incorporate the spending and earnings by regional households into the Leontief inverse matrix, creating an endogenous "household sector". Incorporating the household sector in this way is termed "closing" the model with respect to households. The column coefficients of the "household sector" are the purchases by the household final demand category (this is a column vector in the IO tables) divided by the sum of all payments to wage income (earned across all sectors purchases of labour (x_{n+1})).

$$a_{i,n+1} = z_{i,n+1} / x_{n+1}$$ Equation A10

The additional row for the household sector is calculated as follows. The "household sector" sells labour services to all sectors in the region, and so the row coefficients for the household sector are each sectors purchases of labour services divided by that sectors output.

$$a_{n+1,j} = z_{n+1,j} / x_j$$ Equation A11

Assuming the correctness of the Leontief inverse (Miller and Blair, 2009) the typical work of the IO modeller is therefore to use the matrix to show how regional activity will be disturbed by a change in final demand for sectoral output. For that purpose therefore, the analyst can calculate "multipliers" for each sector in the region, which provide useful shorthand for the impact on measures of regional activity of disturbances to the demand for output of specific sectors. Multipliers calculated under the "open" model are termed Type 1 multipliers. Multipliers calculated under the "closed" model, with households' income and spending endogenised, are termed Type 2 multipliers.

A.2 IO multipliers from three-sector example

	Employment-output		Income-output		GVA-output		Employment-employment	
	Type 1	Type 2	Type 1	Type 2	Type 1	Type 2	Type 1	Type 2
Primary and manufacturing	9.832	15.413	0.357	0.522	0.572	0.831	1.671	2.619
Utilities and construction	10.666	16.352	0.364	0.532	0.660	0.924	1.997	3.061
Services	16.688	24.221	0.482	0.705	0.752	1.102	1.333	1.934

Notes: Employment-output, income-output and GVA-output multipliers for each sector show the change in employment, income and value added respectively from a unit change in final demand for the output of each sector. Employment-output multipliers show the change in jobs (in full-time equivalents, or FTEs) from a £1 million change in final demand for each sectors' output, while income-output and value added multipliers show the impact (in £) of a given (£) change in final demand for a sectors output on income and value added respectively.

Employment–employment multipliers show the effect on aggregate FTE employment of changes in the sectoral FTE employment in each sector. Multipliers are calculated in both Type 1 (“open”) and Type 2 (“closed with respect to households”) configurations, as explained in Section 2.1.1 of the text.