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UKERC Review of Evidence for the Rebound Effect

Technical Report 4: Computable general equilibrium modelling studies

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Preface

This report has been produced by the UK Energy Research Centre's Technology and Policy Assessment (TPA) function.

The TPA was set up to address key controversies in the energy field through comprehensive assessments of the current state of knowledge. It aims to provide authoritative reports that set high standards for rigour and transparency, while explaining results in a way that is both accessible to non-technical readers and useful to policymakers.

This report forms part of the TPA's assessment of evidence for a **rebound effect** from improved energy efficiency. The subject of this assessment was chosen after extensive consultation with energy sector stakeholders and upon the recommendation of the TPA Advisory Group, which is comprised of independent experts from government, academia and the private sector. The assessment addresses the following question:

What is the evidence that improvements in energy efficiency will lead to economy-wide reductions in energy consumption?

The results of the project are summarised in a Main Report, supported by five in-depth Technical Reports, as follows:

1. Evidence from evaluation studies
2. Evidence from econometric studies
3. Evidence from elasticity of substitution studies
4. Evidence from CGE modeling studies
5. Evidence from energy, productivity and economic growth studies

A shorter Supplementary Note provides a graphical analysis of rebound effects. All these reports are available to download from the UKERC website at: www.ukerc.ac.uk/

The assessment was led by the Sussex Energy Group (SEG) at the University of Sussex, with contributions from the Surrey Energy Economics Centre (SEEC) at the University of Surrey, the Department of Economics at the University of Strathclyde and Imperial College. The assessment was overseen by a panel of experts and is extremely wide ranging, reviewing more than 500 studies and reports from around the world.

Technical Report 4: Computable General Equilibrium Modelling focuses upon quantitative estimates of the economy-wide rebound effect available from Computable General Equilibrium (CGE) models of the macro-economy. In addition to summarising and evaluating particular studies, the report aims to identify the strengths and weaknesses of this approach and to make the issues accessible to a non-technical audience.

Executive Summary

Introduction

The impact of energy efficiency improvements may permeate throughout an economy, leading to a series of adjustments in the production and consumption of different goods and services. These adjustments cannot be adequately captured within a partial equilibrium framework but may be explored through the use of Computable General Equilibrium (CGE) models of the macro-economy. CGE models are widely used in the investigation of energy and climate policy, partly as a consequence of the ready availability of modelling frameworks and associated benchmark data. However, these models have rarely been used to study economy-wide rebound effects, despite their apparent suitability for this purpose.

This report clarifies the strengths and weaknesses of CGE models for investigating economy-wide rebound effects, summarises the methodology, results and implications of eight existing studies and highlight priorities for future research.

Strengths and weaknesses of the CGE approach

CGE analysis is grounded in economic theory, but can deal with circumstances that are too complex for analytical solutions. As such, CGE analysis can be considered a numerical aid to analytical thought. In the case of rebound effects, a CGE analysis can simulate the various substitution, income, output and composition effects that may follow from energy efficiency improvements.

CGE models are parameterised to reflect the structural and behavioural characteristics of a particular economy. As a result, they can estimate the order of magnitude of effect that may result from a particular exogenous disturbance, such as an energy efficiency improvement. CGE models have a very well developed supply side, allowing investigation of rebound effects in sectors where empirical evidence is weak and where other models (e.g. Input-Output) are inappropriate. CGE models also make it easier to evaluate the net impacts of an energy efficiency improvement, since the counter-factual is simply a model run without any changes in energy efficiency. Since all changes in output, employment and energy use are measured relative to this baseline, the marginal effects of the energy efficiency improvement are clear. Evaluating the same policy using time series or cross-sectional statistical data would require the counter-factual to be identified by appropriate statistical control, which may be harder, and risks confusing the drivers of changes in energy use.

However, CGE models do have a number of well-established weaknesses. For example, most represent production behaviour through the use of 'well-behaved' but relatively restrictive functional forms, with limited facility for testing their appropriateness. Parameter values for these functions may be assigned through calibration to a base year, but this may not be representative. Alternatively, they may be taken from empirical studies, but these may relate to different countries and/or time periods from that to which the CGE model is applied. While sensitivity tests are feasible, they are not always conducted in practice.

CGE models also assume that firms minimise costs, that consumers maximise utility and that the source and direction of technical change is exogenous. Each is partly inconsistent with empirical evidence. Markets may also be assumed to be competitive and factor inputs may be assumed to be mobile, although neither is a necessary feature of CGE models. While the results of CGE models may sometimes be driven by assumptions that are not readily apparent, CGE models are not necessarily a 'black box'. Transparency may be considerably

improved by providing information on key features and assumptions and explaining the results with reference to economic theory.

Theoretical considerations regarding economy-wide rebound effects

The view that there are no economy-wide rebound effects is implausible. This would require that: first, there was no possibility of substituting other inputs for energy; second, the demand for energy was entirely invariant with respect to its price; and third, the demand for the goods was unresponsiveness to price changes or that the share of energy in the cost of producing those goods was approximately zero. It is difficult to imagine any real world example of such an economy. For similar reasons, theoretical arguments that backfire is impossible can be ruled out. Ultimately the size of the economy-wide rebound effect is an empirical issue and cannot be determined through theoretical arguments alone.

Rebound effects may be expected to be larger when energy can be easily substituted for other factors of production. However, it is incorrect to assume that rebound effects must be small when the elasticity of substitution between energy and other inputs is small. Rebound effects will also be influenced by other factors, including by the price elasticity of demand for the output in which energy is an input. This may be particularly important in economies which are open to trade, since the output produced by the economy may be price-elastic.

Theoretical arguments suggest that the overall impact of a change in energy efficiency may depend largely on the general equilibrium own-price elasticity of the demand for energy. Where this is greater than unity, the fall in the implicit price of energy should generate an increase in expenditure on energy so that overall energy use would rise. The simplicity of this result does not seem to be widely appreciated.

CGE studies of economy-wide rebound effects

Eight CGE modelling studies of economy-wide rebound effects have been identified and reviewed (Table E.1). They vary widely in their simulation of energy efficiency improvements, with some models introducing an across the board improvement and others introducing a specific improvement in an individual sector, or combination of sectors. The models also differ widely in other respects, including: the relevant country or region; the 'nesting structure' chosen for the production functions; the location of energy within this structure; the assumptions made about the elasticity of substitution between energy and other inputs; the extent to which the capital stock is allowed to adjust; and the assumptions made about the elasticity of labour supply and the recycling of government revenues. This diversity complicates the comparison of results.

It is interesting to note that all of the studies find economy-wide rebound effects to be larger than the 'consensus' figure for the magnitude of direct rebound effects, which is 30% or less. The minimum economy-wide rebound found in the CGE studies is 37% and most studies show either large rebounds (>50%) or backfire. The latter was found in two studies of open economies where energy is an important export commodity, suggesting that this is a potentially important but hitherto neglected variable.

Table E.1 Estimated economy-wide rebound effects from CGE modelling studies

Author/Date	Region	Efficiency improvements	Estimated rebound effect
Semboja, 1994	Kenya	Improvements in both production and consumption sectors	>100% in both cases
Dufournaud et al., 1994	Sudan	100-200% improvement in efficiency of in heating stoves	47-77%
Vikstrom, 2003	Sweden	15% in production sectors and 12% in energy sectors	50-60%
Washida, 2004	Japan	1% all sectors	53% in base case
Grepperud & Ramussen, 2004	Norway	Doubling of historical growth rate of electricity productivity for four sectors, and doubling of growth rate of oil efficiency for two sectors	Small for oil, but >100% in some cases for electricity
Glomsrod & Taoyuan 2005	China	Deregulation of coal cleaning industry, lowering price and increasing supply of clean coal	>100%
Hanley et al, 2005	Scotland	5% for producers (including energy supply)	>100%
Allan et al, 2006	UK	5% for producers (including energy supply)	37% in base case

Following Saunders, most of the above studies have emphasised the importance of the elasticity of substitution between energy and other inputs. But Allan et al. show that elasticities of export demand can also be an important driver of results. Other characteristics such the elasticity of supply of capital and labour inputs, the energy intensity of individual production sectors, the elasticity of substitution between consumption goods and the income elasticity of demand for goods are also potentially important.

Theory may help in identifying those parameters potentially influencing the size of rebound effects from particular energy efficiency improvements, allowing them to be explored further through sensitivity analysis. This should be an important part of any CGE study, but existing studies generally conduct much less sensitivity analysis than might be desirable.

Limitations and priorities for future research

Given the environmental and economic benefits that are claimed for energy efficiency improvements, it is surprising that there have not been more CGE studies examining system wide impacts. As a result, there is considerable potential for further research.

CGE models are best suited to exploring the implications of energy efficiency improvements in production sectors. To explore the effect of energy efficiency improvements in consumption activities would require a greater degree of disaggregation on the demand side of CGE models than is commonly the case. CGE models also typically simulate 'pure' energy efficiency improvements which are assumed to be costless. Only two studies have considered the additional costs associated with energy efficiency improvements and these find rebound effects to be correspondingly reduced.

The empirical basis for assumptions regarding key parameter values in CGE models could be improved. There is also scope for informed sensitivity analysis, identifying the full range of results for plausible model closures and highlighting the importance of specific assumptions about the economy under investigation. This would help to show how robust the results are, and with what confidence they can be expressed.

Summary and conclusions

CGE models are a potentially valuable tool for exploring the way in which energy efficiency improvements impact across an economy. They can shed light on the resulting impacts on energy use in a manner that is consistent with economic theory, and internally tractable – allowing the results to be interpreted intuitively. With appropriate use and associated explanations, a carefully constructed CGE analysis can overcome the "black box" criticism. At the same time, careful sensitivity analysis may allow the robustness of results to be examined and help reveal the source of any modelling surprises.

At present, there are only a handful of CGE investigations of economy-wide rebound effects. The existing studies show that economy-wide effects may potentially be large and that the potential for backfire cannot be ruled out. Moreover, these rebound effects derive from 'pure' energy efficiency improvements and therefore do not rely upon simultaneous improvements in the productivity of capital and labour inputs. The CGE results apply solely to energy efficiency improvements by producers, so therefore cannot be extended to energy efficiency improvements by consumers. Also, the small number of studies available, the diversity of approaches used and the limitations of the CGE approach all suggest the need for caution when interpreting quantitative results.

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1 Introduction

There is a keen political and research interest in examining the role of energy efficiency policies in delivering energy and environmental, as well as economic, benefits. A number of modelling techniques have been employed. In this paper, we examine the use of computable general equilibrium models in this role.

In Section 2 we introduce the computable general equilibrium (CGE) method, and discuss the basic principles of this approach. In Section 3 we assess the strengths and weaknesses of CGE modelling and in Section 4 the CGE method is compared to other modelling techniques. Section 5 outlines the rebound effect and introduces the papers which have used the CGE approach to analyse the impact of improvements in energy efficiency. These papers are analysed in more detail in Section 6. In this section, we firstly outline “key features” for CGE models applied to this research question, before examining how these key features differ across the papers identified. In Section 7 we draw together the evidence from the papers to answer some specific questions about the usefulness of the CGE modelling approach in examining energy efficiency policy impacts. Section 8 concludes and suggests some priorities for further research.

2 An Appraisal of Computable General Equilibrium modelling

2.1 Introduction to computable general equilibrium modelling

Computable General Equilibrium (CGE) modelling involves numerically simulating the general equilibrium structure of an economy, where a general equilibrium is characterised by a set of price and output levels across all sectors of the economy such that market demand equals supply in all markets simultaneously. The technique is an important tool in evaluating the economy-wide impact of exogenous shocks, and has proved to be appropriate for economic policy appraisal. CGE modelling has been employed to examine a whole range of policy and other non-policy disturbances in a range of research areas, including questions relating to regional trade agreements (see Lloyd and Maclaren (2004) for a review), public finance (Shoven and Whalley (1984)), tax reform (Jorgenson, 1997) and the distributive impacts on different household groups of policy change (e.g. Bourguignon et al (1991)). Furthermore, it has become the most widely used approach for system-wide analysis of energy-economy-environment issues at both national (Beausejour et al, (1995), Bergman (1990), Bohringer and Loschel (2006), Conrad and Schroder (1991), Goulder (1998), and Lee and Roland-Holst (1997), and Conrad (1999) provides a review) and regional levels (e.g. Despotakis and Fisher (1988) and Li and Rose (1995)).

The flexibility of a CGE framework and inherent transparency of the model structure mean that the system allows for in-depth analysis of a wide range of complex economic scenarios, which is difficult to achieve with other modelling procedures. As with all economic modelling techniques, however, the CGE modelling is subject to a number of limitations, for example in assigning appropriate numerical values to model parameters so as to accurately reflect real-world economic relationships. As such, model results must be considered to be no more than useful insights. These issues will be clarified and explored in greater detail in subsequent sections.

This report aims to present an objective overview of CGE modelling and its applications to the analysis of improvements in energy efficiency. In Section 2.2 we draw on an official HM Treasury report on the principles and practice of CGE modelling (Greenaway et al, 1993).

2.2 The basic principles of CGE modelling

2.2.1 Framework

The framework of a CGE model is made up of an analytically consistent mathematical model of the whole economy. The theoretical base rests on the initial work of Walras (1874) and the existence proof of Arrow and Debreu (1954), elaborated on in Arrow and Hahn (1971). The model structure incorporates explicitly stated equations or "functional forms" that describe the behaviour of all parts of the economy, and the interdependencies and feedback effects between the different sectors. Drawn from established economic theory, these functional forms represent the key characteristics of the economy. Typically they allow for substitution between inputs in production and outputs in consumption, the elasticity being either "hard-wired" in the model or a choice variable for the modeller. The exact choice of model structure is driven by the precise purpose of the model. This will determine issues such as the level of sectoral aggregation, the precise functional form specification and the

treatment of the external sector (i.e. how the model accounts for trade and transfers between economies).

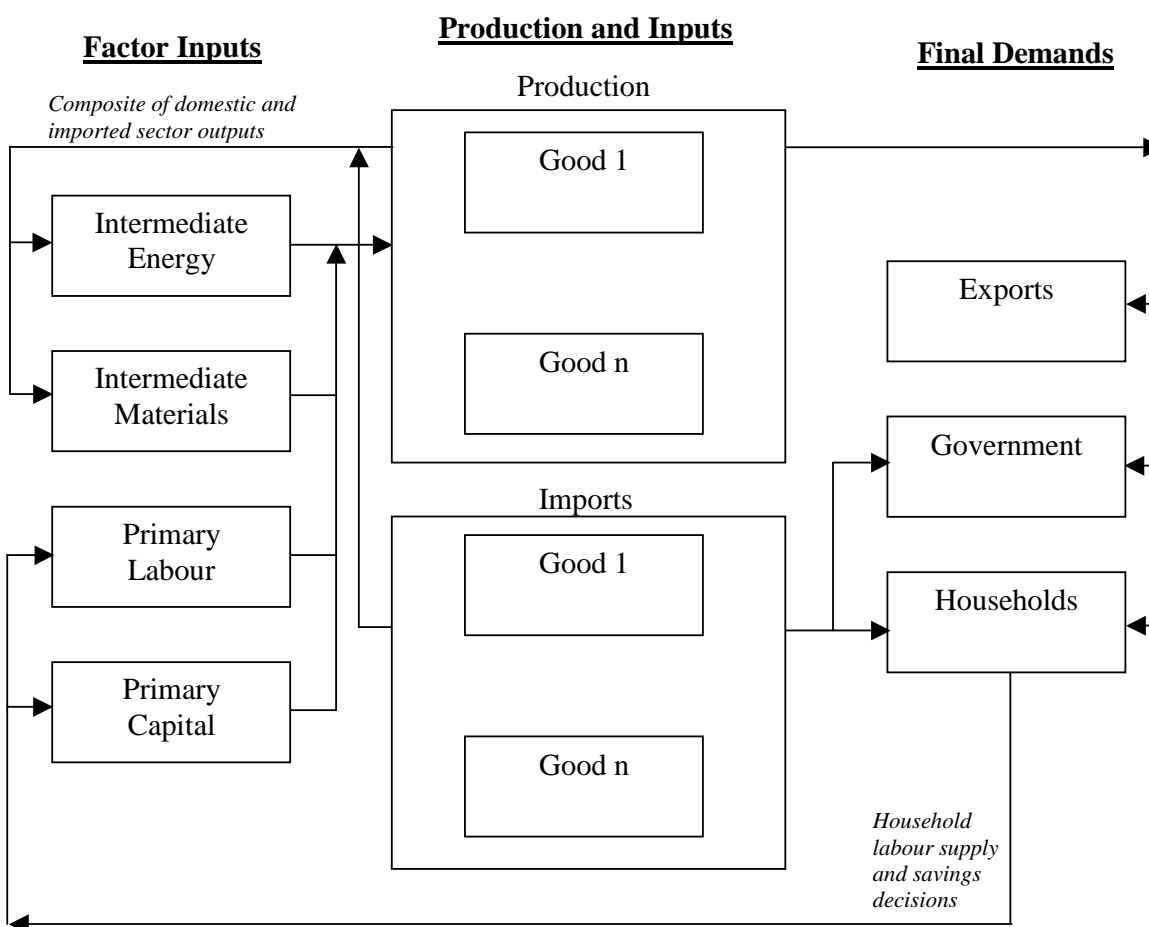
A full description of how a computable general equilibrium model “works” is beyond the scope of this paper, but this has been covered in detail in several publications (Shoven and Whalley, 1984; Conrad, 1999). For the purposes here, we follow Kydes et al (1995) in setting out a simplified schematic diagram of a “typical” CGE model in Figure 1. Advances in computational power (Shoven and Whalley, 1984) have meant that technology is no longer a barrier, and that theories of general equilibrium (Walras, 1874) can now be translated into an empirical context (Greenaway et al, 1993). Technological advances in the mid 1980s made it possible to use general equilibrium techniques to analyse the impact of policy in a more detailed way and to manage the complexity involved in modelling a market economy.

CGE models have their roots in the framework formalised by Arrow and Debreu (1954), and elaborated on by Arrow and Hahn (1971), which is derived from the Walrasian general equilibrium structure. In this structure, the number of consumers is specified, and each has an endowment of commodities and a set of preferences. Utility maximisation allows a set of demand functions to be obtained for each commodity. Total market demand is simply the sum of individual demands. The consumption side of the model is completed by specifying total commodity market demands, which depend on the price level, and which are “continuous, non-negative, homogenous of degree zero and satisfy Walras’ Law” (Shoven and Whalley, 1984, p1009), where Walras’ Law says that the total value of consumer expenditure equals consumer income (Greenaway et al, 1993).

The production side of a CGE model identifies the technology with which firms can produce goods through specifying a production function and assuming that producers maximise their profits or minimise their costs. With zero homogeneity of demand functions and a linear homogeneity of profits with respect to prices, it is the relative – and not the absolute – price level which determines the equilibrium outcome (Shoven and Whalley, 1984). Thus, if all prices double, there is no effect on relative prices, and no effect on the firm’s production decision.

Equilibrium in CGE models is “characterised by a set of prices and levels of production in each industry such that market demand equals supply for all commodities” (Shoven and Whalley, 1984). It is this market clearing principle that characterises the notion of equilibrium in CGE models (Greenaway et al, 1993). Arrow and Debreu (1954) demonstrated that such an equilibrium exists by applying fixed point theorems – such as Brouwer’s theorem or Kakutani’s theorem. Such theorems can be used as “in a general equilibrium framework, certain mappings of the excess demand functions can be shown to provide continuous mappings of the excess demand functions onto itself, whose fixed points, in turn, meet the conditions required for an equilibrium” (Greenaway et al, 1993, p17)

Figure 1: Flow diagram for general equilibrium models



Source: Figure 1 in Kydes et al (1995)

2.2.2 Benchmark data set

Most CGEs are parameterised using a base year Social Accounting Matrix (SAM) dataset for the chosen economy under examination for a chosen time period, generally a year, which provides a "comprehensive and disaggregated snapshot of the socioeconomic system during a given year" (Thorbecke, 2001). A key component of any CGE model is this base year data set. This is typically assumed to represent a benchmark general equilibrium scenario for the economy, and model outcomes are compared to this base year. The benchmark dataset is often the most important feature of an empirical CGE model as it provides this equilibrium position of the economy. The level of aggregation should be selected, together with the base year for which the model is constructed. Modellers tend to derive much of this data set from National Accounts and other official Government data sources.

2.2.3 Parameter values and solution technique

To solve the CGE model, actual values are ascribed to the parameters used in the algebraic functional forms and computational software is used to solve the complex system of interrelated, non-linear equations. Some of the information required are derived from the structural data embedded in a Social Accounting Matrix for the economy under investigation, e.g. relative size, import intensity of sectors, etc. Other data are imposed, e.g. values for elasticities of substitution, trade elasticities or migration functions. With some functional forms it is necessary to pre-specify key parameter values exogenously. This method

involves reliance on careful surveys of existing literature that suggests appropriate parameter values. A final set of parameters are determined through calibration. This procedure involves “fitting” the model to the benchmark data set - choosing the remaining parameters of the model so that the model reproduces the benchmark equilibrium.

2.2.4 Scenario analysis

Once the benchmark data set is fed into the model structure and all parameter values are assigned numerical values, the model can be used for policy evaluation and economic analysis. This involves specifying a new value for one of the variables in the system to represent an economic shock or change in the value of a policy instrument (such as an exogenous expansion in export demand or an increase in the efficiency of manufacturing labour following a Government policy drive to increase manufacturing productivity). The model is solved for the new, alternative equilibrium associated with this change. The structure of the interdependent relationships within the system means that the change in one variable feeds through to the wider economy. The new equilibrium provides an alternative set of price and production levels. These are compared with the benchmark data to evaluate the impact of the economic change across all sectors.

2.2.5 Choice of functional forms

The specific choice of functional forms for utility functions and production functions is a key issue in model design. The choice is driven by both theoretical consistency and analytical tractability, since the chosen functions are required to be consistent with the constraints of a general equilibrium (such as market clearing and normal profits in all markets), while also being able to generate expenditure and production patterns that can be evaluated easily at any set of prices that are judged as a potential equilibrium set (Greenaway et al, 1993).

Some CGE models, indeed all of the models reviewed in Section 6, use nested production functions, with aggregate output for each sector determined through a series of pair-wise substitution possibilities, e.g. value added produced by combining capital and labour, or intermediate inputs combining material inputs or energy inputs. At each stage of the nesting structure it is necessary to specify the type of substitution possible, e.g. a constant elasticity of substitution (typically used, as these allow for substitution) or Leontief forms of substitution (with fixed technical coefficients) in special cases where no substitution between inputs is preferred for the specific modelling purpose.

For considering how to deal with the external sector, initial general equilibrium theory posited that the relationship between domestic and foreign goods was one of perfect substitutes, implying the law of one price. This means that when foreign prices change (or when the domestic price of foreign goods change), the price of competing domestic goods changes by the same amount. Modern CGE modelling has brought in the assumption of imperfect substitution between domestic and foreign produced goods (which is consistent with cross-hauling – countries importing and exporting goods of the same commodity). The degree of substitution between domestic and foreign goods is often modelled using Armington elasticities (Armington, 1969).

3 Strengths and weaknesses of CGE Modelling

In this Section we evaluate some of the general strengths and weaknesses of CGE modelling. This informs our later assessment of specific strengths and weaknesses of the CGE approach for addressing the specific question of energy efficiency improvements, and the extent to which rebound effects may occur.

3.1 Strengths of CGE Modelling

3.1.1 Microfoundations

One key benefit of CGE models is that they are built on solid neoclassical theoretical microfoundations. This means that the behaviour of consumers, producers and the Government and their interdependencies with the wider economy can be explicitly modelled, unlike in many alternative modelling strategies (see Section 4). This brings two key advantages. Firstly, the welfare effects of different policy situations or economic shocks can be explicitly identified using a Pareto measure of welfare that has sound theoretical foundations. Secondly, the approach allows the modeller to identify and compute distributional changes that result from different economic policies or scenarios. Since all policy changes have welfare and distributional consequences, these issues are central to policy appraisal, but are beyond the scope of many other modelling strategies.

3.1.2 Flexible evaluation of policy changes

The ability to assess the impact of changes in the economic environment on both efficiency and equity is particularly useful for economic appraisal: a wide range of economic scenarios, policy options or policy “packages” – composed of a range of complementary reforms – can be considered within a common framework. This flexibility allows the model to be specifically tailored to the research question, and the resulting outcomes can be compared and ranked numerically. CGE models thus provide a framework for assessing ‘second-best’ situations, in which there may be existing market distortions, preventing the existence of a socially optimal economic situation. Such “distortions” in real economies might be taxes or subsidies and imperfections in goods or factor markets (Bohringer and Loschel, 2006). This is crucially important from a policy-making perspective, since ‘first-best’ outcomes may be unachievable due to budget constraints or the absence of policy autonomy, for example. The inherent flexibility of the modelling approach also means that sectors that are of particular interest can be disaggregated into sub-sectors to allow for richer and more focused analysis, subject to data limitations.

3.1.3 Transparency

As Devarajan and Robinson (2002) note, for economic models to be useful for policy analysis, a desirable feature is transparency – “the links between policy variables and outcomes should be easy to trace and explain”. The formal model structure underlying CGE analysis is transparent, and the consequences of using various functional forms can be easily identified, although tracing these consequences through the model is not that common in practice – sometimes leading to accusations that CGE analysis is a “black box” in which results appear but are not explained. Similarly, the numerical parameter values assigned to the functional forms can be altered, and the resulting effects on the model output considered. This “sensitivity analysis” allows the modeller to test the importance of assumptions about functional forms or numerical parameter values for elasticities for the

robustness of the conclusions made. The transparency of the model structure allows the results to be traced through a clear theoretical structure, which provides for sound analysis, i.e. a direct link between the policy being modelled, the approach being employed and an intuitive and clear explanation of the results from simulation. Devarajan and Robinson (2002) argue that there is a natural tension between a desire for transparency on the one hand, and perhaps the use of stylised models, and the policy requirement for sectoral and institutional detail provided by a large and more complex model.

3.1.4 Evaluation of non-marginal changes

Another strength of CGE modelling is the ability to evaluate non-marginal changes. Since many potential policies or economic scenarios are absolute – such as the introduction of a new emissions tax or a significant development in the renewable energy sector – rather than marginal in nature, this trait offers significant insight.

3.1.5 Joint policy appraisal

CGE models can also be used to compute policy alternatives comparatively, e.g. policy disturbances can be modelled in combination as well as individually. This is an important feature for the appraisal of policies, where outcomes across a series of policy measures may have combined impacts which wouldn't be identified from looking at each in turn.

3.2 Weaknesses of CGE Modelling

3.2.1 Functional form constraints

There also exist a number of potential weaknesses inherent in the CGE modelling approach. Although the model structure theoretically allows for the incorporation of any functional form to describe consumers' behaviour, for example, modellers are generally constrained to work with a small number of relatively straightforward and 'well-behaved' functional forms. This constraint arises due to solution method and parameterisation considerations. The functional forms most often used by CGE modellers are, however, widely established in literature as being representative of actual consumption or production patterns. Although sensitivity analysis can determine whether the choice of functional form significantly affects results, there remains no facility for testing the appropriateness of functional forms or the general CGE model structure, except insofar as outcomes are consistent with prior expectations and the modellers' judgement.

3.2.2 Parameterisation

Assigning numerical values to these functional forms brings its own set of problems. Some parameter values are chosen so as to allow the model to replicate the benchmark data set. Other values are taken from secondary sources - external econometric studies, for example - and these estimates may be drawn from different time periods or countries from that which the CGE model is based upon. There is similarly no means of testing the appropriateness of the numerical values assigned to the functional forms. Sensitivity analysis provides some means of compensation, though it has its own shortcomings, mentioned above. Furthermore, there is no guarantee that the benchmark data set upon which the model is based is itself genuinely representative of a true equilibrium to which any new counter-factual model output can be compared. Various attempts have been made to counter some of these weaknesses that related to the calibration process typically used to parameterise CGEs, and are not inherent to CGE modelling, per se.

3.2.3 Calibration

An important issue is that CGE models are often calibrated using data from the SAM. In this calibration process the economy is assumed to be in equilibrium in the base year. Of course, if this is not the case, then some of the parameters of the associated functional forms will be incorrect. For example, if a particular sector is depressed in the base year, the share of profits in the output of the sector would be low. In the calibration process, this would be interpreted as the sector's having a low capital intensity. Perhaps more generally, there will be variations within the economy as a whole across the business cycle that would affect calibrated parameter values in a systematic way.

In practice this is not a serious problem for most developed economies, given the normal variations that occur across the business cycle. However, if it were thought to cause difficulties, there are ways in which it can be countered. For example, the model could be calibrated on a composite SAM that was made up from the combined data for a number of years.

3.2.4 Uniqueness of equilibrium

In the theoretical literature, allowing the most general consumption and production relationships that are consistent with the standard economic approach, it is not possible to show that a general equilibrium is unique or stable (Mantel, 1974; Debreu, 1974). This suggests that an economy driven by conventional economic forces would be unstable. As Ackerman (1999, p.3), asserts: "Cycles of any length, chaos, or anything else you can describe, will arise in a general equilibrium model for some set of consumer preferences and initial endowments."

First, it is important to note that the target of this critique is not general equilibrium modelling as such: it is the whole stable of conventional economic models. Ackerman (1999) is arguing that the actual stability that we observe in developed economies must be explained through some behavioural limitations on individual's actions and that this should be the focus of future research. Second, we are not aware of any work that suggests that operational Computable General Equilibrium models do not have unique equilibria, or that they suffer from instability problems of the type.

However, this raises a slightly different line of attack: that the functional forms CGE models adopt, whilst stable, fail to fully reflect actual consumption or production possibilities. This is argued especially for production relationships, where the substitution limitations of Constant Elasticity of Substitution (CES) production functions are criticised (Saunders, 2006). It is important to state that CES production functions are widely used in economic analysis: they are not a special preserve of CGE modelling. Second, CGE models very frequently use "nested" production functions, where the elasticity of substitution both within and between nests can differ. This gives wide scope and flexibility for modelling particular technologies. Whether we have enough data to model these technologies accurately is probably a more pertinent question, though this is not an issue restricted to the CGE approach.

3.2.5 Dynamic properties and the monetary sector

Other difficulties arise in incorporating dynamic properties into the model (agents' expectations – can agents' behaviour today adapt to how they perceive the future? – and intertemporal substitution, for example). Similarly, monetary sectors tend not to be particularly sophisticated. The model must also be 'closed' against external factors, and this

gives rise to further model specification issues; the model output will be sensitive to the closure rules applied.

Overall, the complex interdependencies and feedback effects between policy instruments and sectors that exist in reality are difficult to model in anything other than a general equilibrium framework. The flexibility and transparency of the modelling procedure make it a useful economic tool, particularly with regard to policy evaluation and economic scenario analysis. The multisectoral structure of CGEs is also particularly useful in the current context, given the substantial variation in energy intensities across sectors. The technique is, however, subject to a number of limitations. The reliance on the modellers' judgement and fairly strong assumptions - that are nevertheless generally supported by economic theory - mean that the outputs should be interpreted as valuable insights rather than absolute fact.

3.2.6 Market and behavioural assumptions

CGEs almost always assume that firms cost minimise and that consumers utility maximise in an atomistic way. Typically commodities and factors of production are bought and sold in perfectly competitive markets, but this is not necessarily the case. For example, some CGE models explicitly adopt imperfectly competitive product markets (and increasing returns to scale). The Dixit-Stiglitz formulation is a popular option. Also CGEs usually differentiate between domestically and externally produced goods. The law of one price typically does not hold, so that foreign and domestic goods are not perfect substitutes. Finally in some CGE models factor markets, and in particular the labour market, are not taken to be perfectly competitive.

3.2.7 Factor mobility and adjustment costs

CGE models exhibit a wide range of degrees of factor mobility. For capital, in some short-run models the capital stock is fixed at the level of individual industries. In others, the capital stock is fixed in the short run but is mobile between sectors to equalise the rate of return. In the long-run aggregate capital stock is frequently driven by the level of domestic savings and is usually freely mobile between sectors. Labour typically can move freely between sectors, even in the short run, but in some models labour mobility across some sectors is restricted.

As indicated above, often CGE models have a one-zero approach to adjustment costs: either they are so high that adjustment is prohibited or so low that it is effectively costless. Some models do incorporate adjustment costs in period-by-period simulation.

3.2.8 Time scales

CGE models usually follow the Marshallian definition of the long run as a conceptual time period where all adjustments have taken place. This is especially important for adjustments to the capital stock. Where models give long-run results one would have to run these models in a period-by-period mode in order to assess how long this would be in real, as against conceptual, time.

3.2.9 Technical change: how is autonomous technical change modelled?

In the CGE approach the natural way to model a change in energy efficiency is to increase the effective energy services that one unit of energy delivers. This energy unit is typically some energy composite. This has the advantage of pinpointing the 'pure' energy efficiency

effect; typically no cost is attached to the energy efficiency change. Some studies introduce an across the board, equal change to all sectors but this is not a necessary characteristic of the CGE approach: energy efficiency shocks can be imposed on individual elements of production and consumption or at different rates across different activities. Some CGE studies attempt to replicate the operation of actual energy efficiency policies and these are likely to incorporate some element of implementation cost.

4 Comparison between CGE modelling and other modelling techniques

For the purposes of evaluating economic or policy changes, CGE analysis offers considerable advantages relative to other modelling techniques. Some alternative modelling methods, in contrast, address the weaknesses of CGE analysis. All advanced modelling approaches face constraints, however, due to the complexities and uncertainties involved in capturing detailed economic systems accurately.

4.1 Partial equilibrium modelling

Time series modelling¹ involves analysing actual data series in order to consider the expected behaviour of an economic indicator based on its past performance. By analysing past data, this technique can be used to predict how the values of economic variables may change over time in the absence of economic shocks. They can provide a useful benchmark for assessing the forecasting ability of more detailed econometric models, and, like CGE models, they can account for interactions between sectors. In themselves, however, time series models don't provide a theoretically satisfactory description of the whole economy, and so are not suitable for providing a sufficient interpretation of the consequences of economic policies.

4.2 Simple general equilibrium modelling

Simple general equilibrium modelling and partial equilibrium modelling, in comparison with time series analysis, do provide important insights into the potential effects of economic policy. They are based on the same principles and framework as standard CGE modelling, though simple general equilibrium modelling adopts a set of equations that represent a more simplified version of the whole economy, while partial equilibrium modelling attempts to model only part of the economy. Both techniques can allow for policy ranking to some extent, but are more suited to providing the underpinnings for CGE analysis: simple general equilibrium modelling is insufficiently detailed to represent a real economy, whilst partial equilibrium modelling, by its nature, excludes relationships and interdependencies which could be central to policy evaluation. It should be mentioned that there is a spectrum of general equilibrium models ranging from models that are essentially "theory with numbers" at one end, to attempts to track real economies at the other end.

4.3 Fixed-Price General Equilibrium Modelling

Modelling techniques that offer a richer specification of the economy, akin to CGE modelling, include economy-wide 'fixed-price' models, such as Input-Output models and Social Accounting Matrices². An I-O model in its most basic form consists of a system of linear equations, each of which describes the distribution of an industry's production throughout the economy. The model is constructed using observed data for each sector, and its fundamental purpose is to analyse the interdependence of industries in an economy. The

¹ For an accessible discussion of key aspects of time series analysis, see Mills (1992). For a more technical treatment of the issues see Lucas (1976).

² Armstrong and Taylor (2000) and Miller and Blair (1985) each provide a comprehensive overview of this modelling technique.

system allows for 'what if' scenario analysis, and is mathematically straightforward to solve. It is, however, subject to very restrictive assumptions: I-O models cannot simultaneously model prices and quantities, or supply and demand. Thus the assumption is often made that price adjustments do not occur, or that the supply side is passive, and the resulting effects of changes in these variables are excluded from the analysis. In essence, I-O is effectively a very simple CGE that only applies, in its usual specification, when the supply side is, for some reason, entirely passive. Furthermore, the system, so modelled, does not allow for substitution between factor inputs – for example in response to changes in the relative price of labour and capital. These unrealistic assumptions provide key limitations relative to CGE modelling. Since policy makers will be concerned with price changes and their economy-wide effects, I-O modelling provides a less thorough analysis of the effects of economic and policy changes than CGE analysis.

4.4 Macroeconometric models

Formal macroeconometric models provide a much more comprehensive explanation of whole-economy responses to changes in economic conditions than the alternative modelling techniques mentioned so far. Like CGE models, macroeconometric models are made up of a set of equations that describe the economy and are based on economic theory. The coefficients within the equations are estimated using actual data on the variables and appropriate econometric techniques. The coefficients within the equations are estimated using actual data on the variables and appropriate econometric techniques. The models have strong theoretical underpinnings, and since they are estimated based on established statistical procedures, there is scope for measuring the confidence in model results and for testing the appropriateness of functional forms and parameter values. Time and data constraints will significantly constrain the extent of such analysis, but this nevertheless provides a significant advantage over CGE modelling, where the possibility for diagnostic testing is limited.

Econometric modelling potentially offers other significant benefits over CGE analysis, at least in principle, particularly in its ability to deal with dynamic issues - such as the depletion of resources and accumulation of capital over time - and also in its ability to incorporate monetary relationships into the system³. CGE modelling offers less sophisticated techniques for dealing with these issues.

Nevertheless, macroeconometric modelling suffers from limitations. The microeconomic structure of the economy tends to be less detailed relative to the CGE analysis, and thus less insight is provided regarding the consequences of policy changes on welfare and equity in society.

4.5 Dynamic optimisation and optimal control

Dynamic optimisation and optimal control (DO/OC) models also offer a good modelling alternative to CGE analysis. Such models similarly offer an economy-wide evaluation of the consequences of economic reform. These models are also based on a set of structural equations that represent established economic theory, and are designed to track the movement of the economy over time. They are well founded in economic theory, and recent advances in research mean that they can offer detailed representations of the

³ Rotemberg and Woodford (1997) present an influential econometric framework for policy evaluation.

microeconomy. Their use is widespread – from financial economics to business cycle analysis - but their ability to incorporate particularly detailed monetary sectors mean that they are prevalent in monetary policy analysis literature.⁴ Like macroeconomic modelling, however, they offer a less flexible vehicle for analysing distributional and welfare effects – matters of central concern to policymakers.⁵

The complexity of the model specification and solution method for DO/OC models also present limitations for modellers: parameter estimates often need to be taken from sources outwith the system, leaving the technique open to the same restrictions as CGE modelling, and they are less flexible than CGE modelling for analysing a variety of 'what if' economic scenarios.

Overall, each of the modelling techniques offers significant contributions to policy evaluation, particularly CGE, macroeconomic and DO/OC analysis. These models face common constraints - especially in modelling expectations and forward-looking behaviour, in striking a balance between specifying a sufficiently detailed model structure and the need to allow for model solution, and also with relation to time and data constraints that restrict sensitivity analysis or the testing of model results. Furthermore, the nature of the inexact relationship between economic variables means that the intuition and sound judgement of the modeller plays a crucial role in each of the modelling processes.

In some cases, the specific weaknesses of one model may be compensated for to some extent by the strengths of another. Macroeconomic and DO/OC models may therefore be best seen as complements to CGE analysis, rather than alternatives. In principle, some of the weaknesses of calibrated CGEs may be overcome by employing some of the other modelling approaches. However, the data requirements of this are such that there is as yet no complete econometrically estimated CGE. Nonetheless, the approaches are likely ultimately to converge.

⁴Informative studies that employ dynamic optimisation models for monetary policy evaluation include Calvo (1983) and Clarida, Gali and Gertler (1999).

⁵ The objective of dynamic optimisation models differs significantly from those of CGE models. Dynamic optimisation models seek to optimize a set of inputs and values given specific policy objectives. In contrast, CGE models simulate the effects of a change in a n economic variable, often with a view to considering the effects of a potential policy. Thus the appropriateness of each modelling technique differs according to the objective of the economic research, as is the case across all modelling alternatives.

5 CGE modelling, energy efficiency improvements and rebound effects

5.1 The rebound effect

While the original source of the term “rebound” is uncertain, a literature has grown in the modern energy economics literature around the impacts that improvements in energy efficiency will have on energy demand. In this literature the argument that improved energy efficiency might not result in reduced energy use has been termed the Khazzoom-Brookes postulate. This has centred around the possibilities of “rebound” – when energy use falls by less than the improvement in energy efficiency – and “backfire” – when energy use actually increases following the energy efficiency improvement (Greening et al, 2000). Both Khazzoom (1980) and Brookes (1990) acknowledge the intellectual debt this literature owes to the early work of Jevons (1865). In his work, Jevons (1865) focuses on the possible exhaustion of a finite natural resource, namely coal. In a key passage, examining the argument that a more efficient use of coal would prolong its life, Jevons (1865, p140) writes, “it is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth”. This argument has been used again to counter the resurgence in policy arguments that energy efficiency can reduce our dependence on oil (as criticised by Brookes, 1978) or limit environmental impacts (Pearce, 2001). Wilhite and Norgard (2004, p992) argue, echoing Jevons, “the policy and the research at the centre of the discourse on energy sustainability suffer from a self-deception, which revolves around the equation of ‘efficiency’ with ‘reduction’”.

A number of papers, such as Sorrell and Dimitropoulos (2005) have described the range of approaches used to quantify the empirical scale of the rebound effect. These approaches vary from direct measurement studies, where potential energy savings are compared to actual energy savings, to quantitative estimates of price elasticities, such as the elasticity of energy service demand with respect to the unit cost of energy (e.g. as in Khazzoom, 1980). Life cycle analysis, decomposition analysis and neoclassical growth theory approaches have also been used. In this report we focus on computable general equilibrium modelling applications.

5.2 Use of CGE models for analysing the impact of energy efficiency improvements

Computable general equilibrium models may be used to investigate the size of the economy-wide rebound effect. We do not argue that finding empirical evidence of rebound or backfire requires such a modelling approach. Where the technological improvements are restricted to one small sector a general equilibrium approach may not be suitable. However where the policy or technological improvement is specifically designed to have impacts that are felt across all industrial sectors of the economy, such as policies targeted at improving energy efficiency, a general equilibrium approach is appropriate and necessary.

Allan et al (2006, p16) describe the system-wide impacts of an increase in resource productivity. In their analysis, show that “the overall impact of a change in energy efficiency depends solely on the general equilibrium own-price elasticity of demand for energy. Where this is greater than unity, the fall in the implicit price of energy will generate an increase in expenditure on energy so that overall energy use would rise: substitution and output effects would dominate efficiency effects”. This is an incredibly simple result, but one in which other

issues arising from the rebound debate can be clarified (see Allan et al (2006) for an exposition of the calculation of this result in a CGE framework). Their result is from what is effectively a macroeconomic analysis of a "good" model. The issue then becomes, once you allow for many sectors within a CGE model, what ultimately governs the general equilibrium own-price elasticity of demand for energy?

Allan et al (2006) use the simple example of an economy which produces a single output through combining two inputs, "value-added" (in turn produced by capital and labour) and an intermediate energy composite. This is similar to that employed by Saunders (2000a) macroeconomic production function analysis, but while that paper effectively adopts a closed economy neoclassical growth model, this can be extended to capture openness by modifying the demand side of the model to recognise the price-elasticity of demand for the single output. Such a framework makes it possible for us to derive the macroeconomic demand for energy as a derived demand for a factor of production. The demand for energy (and labour and capital) in this system derives solely from the demand for the country's output (since we assume here for simplicity that energy is consumed only as an intermediate good). Hicks's (1963) laws of derived demand can be used to identify the determinants of the price elasticity of demand, since rebound is nothing other than the absolute value of the price elasticity of demand in efficiency units.

This approach allows several issues within the rebound literature to be clarified. Firstly, Saunders (2000a) argues that rebound and backfire are "apparently" more likely the greater is the elasticity of substitution of energy for other inputs (e.g. labour and capital). In fact this is one of Hicks's "Rules of Derived Demand", so this result is general in the sense that it is not dependent on the specific production function considered by Saunders. As energy efficiency increases, and the price of an efficiency unit of energy falls, the greater the ease with which energy can be substituted for other factors, the greater the stimulus to energy demand. It has been argued (Allan et al, 2006) that in such a context, rebound, or the price elasticity of demand for energy in efficiency units, does not depend only on the elasticity of substitution of energy for other inputs. Indeed, even if this elasticity is precisely zero, as with Leontief technology, rebound and backfire remain perfectly feasible conditions, if less likely. There appears to be a widespread, but mistaken, belief in the literature that low elasticities of substitution between energy and other inputs imply that rebound must be small and backfire impossible.

Secondly, by neglecting openness from the demand-side one loses sight of the result that rebound is increasing in the price elasticity of demand for the output in which energy is an input. The significance of this result is moderated by energy's share in the relevant scale variable (most commonly GDP), which is typically of low scale. For the particular subject economy however, as we shall see in Section 6 (e.g. in Hanley et al, 2006), openness to trade may imply a highly price-elastic demand for the output produced by the economy. Allan et al (2006) conclude that this implies that the derived demand for energy within a subject economy may also be price-elastic. In these circumstances an economy-specific stimulus to energy efficiency reduces the price of an efficiency unit of energy and hence the goods produced, so stimulating the demand for output, resulting in significant rebound and potentially backfire.

Finally, the price elasticity of demand for energy will also be greater when the elasticity of supply of other factors is greater. These elasticities, such as for capital or labour, will obviously increase with the duration of the time period under consideration. Labour, for instance, could increase through greater participation, longer hours or through in-migration. Capital stocks could increase through investment. These processes will be necessarily

gradual over time, and so time itself may be a very important factor in governing the scale of rebound.

Some other opinions in the existing literature can be addressed using this approach. Firstly, the view that any rebound is unlikely can be ruled as this would require not only energy to be combined with other inputs through Leontief technology, but also that the demand for energy is entirely invariant with respect to own price and that relevant goods' demands be completely unresponsiveness to price changes, or that energy's share in the relevant composite be approximately zero. It is difficult to imagine any real world example of such an economy, and is even less likely for small open economies (largely the focus of empirical estimate of rebound using CGE models, as we shall see in Section 6). We can also rule out theoretical arguments that backfire is impossible as groundless. As Allan et al (2006, p20) conclude, "this is an empirical issue, dependent on the price elasticity of the system-wide demand for energy being greater than unity in the specific context".

Allan et al (2006) make some qualifications or extensions to this basic argument, acknowledging the necessarily simplicity of the general argument. Firstly, energy will be demanded as a final good (households will also demand energy for heating and lighting) as well as an intermediate good. This will simply create further substitution and income effects, matching the output and substitution effects on the supply side, which will tend to provide reinforcing arguments for rebound and backfire. Consumers may substitute towards energy intensive goods in the face of an efficiency-induced fall in the relative price of energy, and real incomes rise, further stimulating the demand for normal goods (including, both directly and indirectly, energy goods). Saturation effects could limit the tendency for the demand for energy to increase as a consequence of incorporating households' behaviour directly, and it is almost certainly the case that substitution possibilities will be more limited for households. Further, it is possible that the responses may not be symmetric in the face of energy price rises or falls, reflecting, for example, adoption of new technologies not easily reversible in response to energy price hikes. The argument here is that the scope for rebound and backfire in response to energy efficiency improvements should focus on the elasticity with respect to price falls, which would be lower than that with respect to price rises.

Further, the usefulness of the simple macroeconomic production approach to rebound will be tempered by several conditions. In practice, there is not one output good but many, with wide variation in energy intensities of production and substitution and demand elasticities, introducing a wide diversity of relative price changes in response to energy efficiency stimuli. Further, there are a range of energy inputs, with substitution possible between them. Such observations would appear to illustrate the usefulness of studies conducted at the sectoral level, and against aggregate studies. With such complexity, a solely analytical approach cannot capture all the structural (e.g. input intensities) and behavioural (e.g. substitution) parameters. This provides part of the motivation for employing CGE modelling approaches for examining this issue.

5.3 CGE studies of the economy-wide rebound effect

In their survey of the rebound effect, Greening et al (2000) found only one modelling study that examined the economy-wide effects of improved energy efficiency (Kydes, 1997). As Greening et al (2000, p397) noted, prices in an economy will undergo numerous, and complex adjustments. Only a general equilibrium analysis can predict the ultimate impact of these changes". Since Greening et al's (2000) review several papers have been published

that use CGE models to analyse the system wide impacts of improvements in energy efficiency.

In the following sections we examine these papers in turn. Our aim is to highlight any similarities between analyses, and to underscore differences across modelling approaches or in terms of the mechanisms through which the results in each case are achieved. Such an approach is intended to draw out similarities or differences in the techniques employed, and identify cases where "best practice" has been employed. Subsequently in Section 7 we provide information on lessons learned from examining each paper in detail, including a checklist of features that would be desired in a CGE model applied to energy efficiency research. In Section 6, we examine a total of eight papers, the last six of which have been published since 2000. The first two papers are older examples of the general equilibrium method applied to specific energy efficiency policies in two developing (African) countries and provide a useful comparison with the more recent papers. The papers are listed in chronological order in Box 5.1.

Box 5.1 CGE modelling studies of the economy-wide rebound effect

1. Semboja, H.H.H. (1994), "The effects of an increase in energy efficiency on the Kenyan economy", *Energy Policy*, March 1994, p217-225
2. Dufournaud, C.M., Quinn, J.T., Harrington, J.J. (1994), "An applied general equilibrium (AGE) analysis of a policy designed to reduce the household consumption of wood in the Sudan", *Resource and Energy Economics*, Vol. 16, p67-90
3. Vikstrom, P. (2004), "Energy efficiency and energy demand: a historical CGE investigation on the rebound effect in the Swedish economy 1957", paper presented at Input-Output and General Equilibrium Data, Modelling and Policy Analysis, Brussels, 2nd-4th September 2004
4. Washida, T. (2004; 2006), "Economy-wide model of rebound effect for environmental policy", paper presented at International Workshop on Sustainable Consumption, University of Leeds, March 5th-6th 2004 and also presented at ERE W3 conference, Kyoto, Japan, July 2006
5. Grepperud, S. and Rasmussen, I. (2004), "A general equilibrium assessment of rebound effects", *Energy Economics*, Vol. 26, p261–282
6. Glomsrød, S. and Taojuan, W. (2005), "Coal cleaning: a viable strategy for reduced carbon emissions and improved environment in China?", *Energy Policy*, Vol. 33, p525-542
7. 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*, Vol. 31, p161-171
8. Allan, G.J., Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2006), "The macroeconomic rebound effect and the UK economy", report for DEFRA, May 2006

We examine each of these papers under a number of common headings, detailed below. In Section 7 we use these papers to answer some specific questions about what can be learned from the experience to date of using CGE models to examine the scale of the rebound effect. We also outline some benefits and some drawbacks of using a CGE approach to answer questions about the economy-wide impact of energy efficiency improvements.

6 Review of existing studies of rebound effects using CGE models

In Section 5 we reviewed some of the literature in the “rebound” debate and saw that there have been a number of studies that have used computable general equilibrium (CGE) methods. Before any conclusions can be made about the usefulness of CGE modelling for estimating the impacts of improvements in energy efficiency policy, we need to examine the methodologies employed in each of these papers. To enable us to compare models across papers we identify the details of the model across “key features”. In Section 6.1 we list these key features, while in Section 6.2 we discuss each feature in turn and identify how they differ across the CGE papers. Section 6.3 summarises the results of each paper comments on their quality. The aim of this section is thus to see the extent to which we can identify common approaches across the models used, and identify “best practice” in modelling the impact of energy efficiency improvements using a CGE approach.

6.1 Key features of CGE models used for rebound analysis

There are several criteria on which we might attempt to evaluate differences in which a CGE model is designed and used. In this section we explain six such criteria. Research to date has shown that these are important for the resulting estimates of the impact of energy efficiency improvements on energy use. The six features explained in this section are:

- treatment of energy in the production function
- elasticity of substitution with energy in production
- capital closure
- treatment of the labour market
- how increased government revenue (from increased economic activity) is recycled
- the way in which the energy efficiency improvement is modelled

We now explain why these features have been selected as important for the CGE models considered.

6.1.1 Treatment of energy in the production function

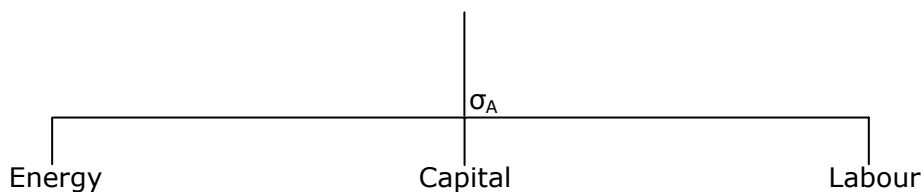
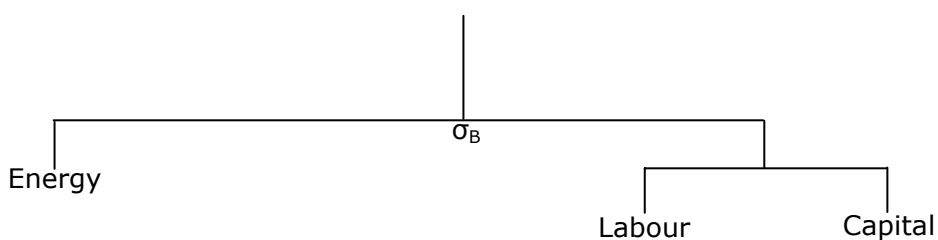
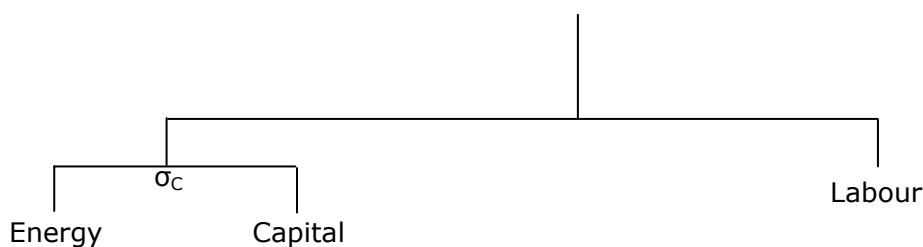
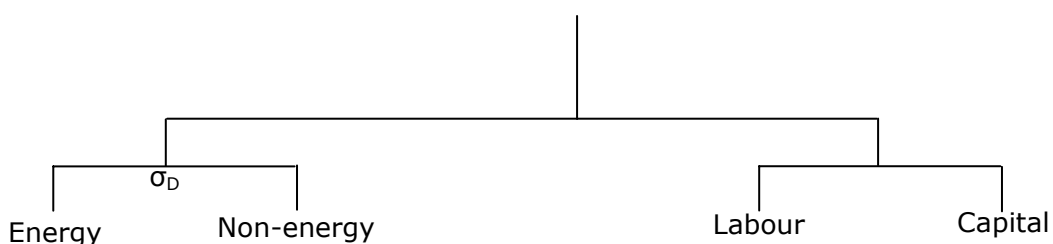
During construction of the CGE model, the developer will be required to specify the structure of inputs to production and consumption. This normally takes the form of specifying a production or consumption function in which there are substitution possibilities between different inputs. Within CGE models featuring labour, capital and energy inputs there are a range of alternative specifications for a production function which allows some substitution between these inputs. It might be expected that where energy is included in such a production function will have implications for the model results, given that it is energy efficiency which is stimulated in each case. We therefore need to acknowledge the different ways in which energy might be included alongside labour and capital in a production or consumption function. We provide four types of such functions here, focusing only on production functions that are used in the papers studied, in which energy enters as an input into production.

In function A, energy is directly substitutable for both capital and labour. Such a production function might represent a case where we have these three inputs combined in a three input Cobb-Douglas production function. Semboja (1994a) and Glomsrød and Taoyuan (2005) use this specification. In function B, energy substitutes with a “value-added” composite formed by a combination of labour and capital inputs. This treatment is used in Washida (2004). In

function C, energy and capital combine to produce a energy-capital composite which is then substitutable with labour, as used by Vikstrom (2004) and Grepperud and Rasmussen (2004). Function D shows a case where labour and capital are combined to form a "value-added" composite and energy and non-energy inputs combine to form an intermediate input composite. Such a treatment is used by Hanley et al (2005) and Allan et al (2006).

As has been acknowledged in most of these papers, there is no consensus in the CGE literature on where the appropriate place for energy is in the production structure. The choice in the literature is generally to have energy substituting with primary inputs, most commonly capital (such as in function C below or Bergman, 1988, 1990). Alternatively, energy can be combined within the intermediates nest (as in function D or Beauséjour et al, 1995). We shall see that the lack of consensus in the CGE literature is, unsurprisingly, carried over into the models we consider.

Figure 1: Alternative specifications for production functions involving energy

Function A**Function B****Function C****Function D**

For exposition, it should be noted that each combination of two goods is normally termed a "composite" good, e.g. an energy-capital composite substitutes with labour in function C. The symbol σ in the figure above correspond to the Hicks elasticity of substitution between the energy good and the other good with which it substitutes.⁶ In some models, the function shown above corresponds to only a section of the overall production structure. In this case we shall detail which part of the production function is created at the level above which

⁶ See *Technical Report 3* for an in-depth discussion of the definition and measurement of elasticities of substitution.

energy enters, for instance, function C might constitute the overall “value added” composite, which is then substitutable with non-energy intermediate inputs.

Within a nested production function, the energy composite good may be formed by a combination of a number of energy inputs, or the output of several energy sectors. For instance, the energy composite in Washida (2004) is formed from a combination of oil, coal, gas and electricity inputs. Substitution between these inputs will generally be a feature of the composite energy good. The specific method by which the energy composite is constructed is less important for this report, as the improvement in energy efficiency which is modelled in the majority of papers, is introduced at the level of the energy composite itself and not on one specific energy input.

6.1.2 Elasticity of substitution with energy in production

There is an acceptance in the literature to date that the elasticity of substitution of energy for other inputs is important for the scale of the rebound effect estimated. What is less agreed, however, is the extent to which this is the most important elasticity (as described in Section 5 and Allan et al, 2006). Thus, we detail the specific value of the substitution parameter in the production function in each paper (e.g. the value of σ_A , σ_B , σ_C , σ_D parameter in figure 1 above).

6.1.3 Capital closure

One crucial component of the CGE model constructed is how capital is specified in the model. The standard Marshallian view on the distinction between the short run and long run is interpreted as, in the short-run capital stock is fixed, while it is fully adjustable in the long-run. Thus, we provide details of the capital closure used in the models. – i.e. is this fixed in aggregate or at the level of individual sectors, or does it dynamically adjust to changes in returns on capital across sectors with investment expanding the aggregate capital stock? Within the papers studied there are gradations: the total capital stock is fixed in some, but variable across sectors; the total capital is variable, but is linked to domestic savings; the total capital is variable, but the allocation across sectors is fixed to base year sectoral shares.

6.1.4 Treatment of the labour market

A number of the recent studies have shown while an energy efficiency improvement can act as a beneficial supply-side policy improving the productivity of one input to production, this can have impacts on the labour market. It is important therefore to specify how the studies here model the labour market it this will have important consequences for the estimated scale of the rebound effect. Some models, for instance, might assume an entirely passive labour supply schedule, while other might assume that labour supply is fixed.

The key link here is between the labour supply and the real wage. Where labour supply is fixed, a positive supply-side policy such as an increase in the efficiency of energy use would lower the real wage but would not engender knock-on effects in terms of employment. If however, there was a labour supply which adjusted to real wages there could be additional rebound effects from increased demand for labour.

6.1.5 How increased government expenditure is recycled

All of the studies model energy efficiency improvement as one which acts as a beneficial supply-side improvement. The papers on the two developing countries acknowledge the development potential of this, as it expands scope for economic output, growth and employment – and taxation revenues. One recent study (Allan et al, 2006) has shown that the way in which government revenues from this extra economic activity are recycled back to the economy can be important. In some models increased government savings might be channelled to investment, while in others this link might not be made. This could have important implications for the scale of the estimated rebound effect; hence we discuss the closure assumptions made in each model.

This recycling has the potential to have obvious demand side implications through increased government expenditure, but also may have supply side implications, for instance in the case where increased government savings are recycled through savings and investment (increasing demand for capital goods and increasing capacity).

6.1.6 The way in which the energy efficiency improvement is modelled

It will be crucial for the results of each model how the improvement in energy efficiency is modelled. Generally, as said above, this will be a step change in the production efficiency of the energy composite good within the production function (or households consumption function in one paper). This stimulus might be across all sectors, or directed to a number of sectors. Looking at this feature of each model lets us identify the extent to which there are differences in this most important item. There is a crucial distinction to be made here between those models which the energy efficiency improvement is a notional change in efficiency – e.g. an across the board stimulus – against those papers where there is a precise energy saving improvement which is attempting to simulate of a specific policy. Crucially, for estimating the size of the economy-wide rebound effect we also need to know the extent to which energy efficiency has been improved.

6.2 How the key features differ across CGE models used for rebound analysis

Having detailed the features that we will focus on, we now turn to describing how these differ across the eight papers in which CGE models are employed to examine the impacts of improvements in energy efficiency.

6.2.1 Treatment of energy in the production function

As explained in Section 6.1.1, there is no consensus on the appropriate place for energy within the production function. This has been reflected in the different approaches for incorporating energy in the papers reviewed here. Of the four types of functions shown in Figure 1 we can conclude that there are two papers (Semboja, 1994a and Glomsrød and Taoyuan, 2005) that include energy in a function **A**-type arrangement. In Semboja (1994a), electricity, other fuels, capital and labour combine together to produce a composite which substitutes with an intermediate composite (consisting of basic inputs and materials). In Glomsrød and Taoyuan (2005), energy, capital and labour combine in the production of a value added composite.

A **B**-type of production function in Figure 1 is found in Washida (2004). In this, energy combines with a labour-capital composite to form a composite good which combines with other intermediate inputs to form gross output goods in each sector. Function **C**-type production functions are found in Vikstrom (2004) and Grepperud and Rasmussen (2004)

where energy combines with capital directly, and then this energy-capital composite substitutes with labour in production of value added. Function **D**-type production functions are found in two papers that use similar CGE models, namely Hanley et al (2005) and Allan et al (2006). In these papers, energy substitutes with non-energy to form a composite which in turn is substitutable with a value added composite of labour and capital.

The paper by Dufournaud et al (1994) is different from the papers above in that energy is not assumed to be an input into production. In this paper, there are two alternative specifications of the households' utility function. In the first one, energy inputs substitute with leisure, while the second utility function assumes that energy substitutes with a composite consumption good.

What can be concluded about the extent to which the place in the production function in which energy enters affects results? We note that both papers which use **A**-type functions see rebound in excess of 100%, however without looking at the other key features, we cannot conclude that this result is in any way explainable by the treatment of energy in the production function. These papers also use Cobb-Douglas as the functional form, which is probably more important for the backfire result in these papers.

6.2.2 Elasticity of substitution with energy in production

Having seen the differences across the papers in which energy inputs are considered within the model, we now consider the differences in the elasticities of substitute of energy for other inputs. Given the variation in the nature of the goods that energy is assumed to substitute with, these values will not be comparable across studies.

Commonly, the CGE papers reviewed here use a constant elasticity of substitution specification between energy and the other good it is substitutable with. The nested CES structure used in every paper allows elasticities of substitution to vary between different inputs. In Washida (2004), where energy substitutes with value added, this elasticity takes a value of 0.5. In Grepperud and Rasmussen (2004) and Vikstrom (2003), where energy substitutes with capital, different values of the elasticity of substitution are used within each sector. In the case of Vikstrom (2004) these values are taken from contemporary surveys of the relevant literature, and range from 0.07 to 0.87 for each sector. In Hanley et al (2005) and Allan et al (2006), energy and non-energy composites substitute with a constant elasticity of substitution of 0.3 for all sectors.

In Semboja (1994a) and Glomsrød and Taoyuan (2005) energy combines in a production function which has Cobb-Douglas substitution between inputs, i.e. the production function (in the case of Glomsrød and Taoyuan, 2005, for the production of value added using energy (x_1), capital (x_2) and labour (x_3)) will be of the form:

$$f(x_1, x_2, x_3) = Ax_1^a x_2^b x_3^c$$

where the parameters a, b and c measure how much the amount of output changes to changes in the inputs.

6.2.3 Capital closure

We would expect that in each paper we study, we would find a clear explanation of the specification of the capital market and how it is closed, given the importance of this in a conventional CGE model. What we are able to say from the papers reviewed is that there is opaqueness in how a number of the papers explain the capital closure of the model. The conventional Marshallian view of the short- and long-runs means that it is important that we

know whether capital is fixed or fully adjustable. This is often not clear from the description of the models that we have reviewed. In the papers where the specification of the capital market is clear, we see that there is considerable differences in the assumptions made.

In Dufournaud et al (1994), sectoral capital is fixed exogenously, so we can say that this is a short-run model, while in Hanley et al (2005) and (the long-run simulations in) Allan et al (2006) sectoral and total capital stocks adjust fully in the long-run. In Vikstrom (2004) capital appears to be adjustable in the long run, but the sectoral composition of the aggregated investment good is fixed in line with the initial benchmark dataset, and so wouldn't respond to differences in the sectoral returns on capital. In Washida (2004) it appears that the aggregated capital stock is fixed, although this is not entirely clear from the exposition. In Grepperud and Rasmussen (2004) it is argued that the model used is a long-run model with capital mobile, so we assume that this means that the total and sectoral capital stock will adjust and a long-run equilibrium will be reached. In Glomsrød and Taoyuan (2005), there is no capital market, it is argued given the peculiarities of the Chinese economy being studied, but the model allows investment to be allocated to sectors based on each sectors share of capital in the base year, like in Vikstrom (2004). Details of the capital closure in Semboja (1994a) are unclear.

6.2.4 Treatment of the labour market

As with the capital market closure, the treatment of the labour market in each of the papers could be crucially important for the results, but the relevant assumptions are not always transparent. In the energy efficiency simulation reported in Vikstrom (2004) and Washida (2004) it appears that there is a fixed aggregate supply of labour. An entirely opposite labour market specification is used in Glomsrød and Taoyuan (2005) where it is assumed that there is an exogenous real wage with an infinitely elastic labour supply. Again, as with the capital market specification, this paper argues that this is appropriate in the case of China, where there is assumed to be a ready supply of additional labour through population growth and closedowns of state-owned enterprises.

In Hanley et al (2005) it is assumed that wages are subject to a bargained real wage function in which the real consumption wage is directly related to workers bargaining power, and therefore inversely related to the unemployment rate (e.g. Minford et al, 1994). Regional migration is also a function of this model of Scotland where net in-migration is assumed to respond to differences in the real wage and the unemployment rate between Scotland and the rest of the UK. Allan et al (2006) use a similar bargained real wage labour market specification in their central simulation, but use two special cases of the labour market in sensitivity analysis – a case when there is an exogenous labour supply (implying “a completely wage-inelastic aggregate labour supply function”) and a second case of a fixed real wage closure (in “which total employment changes to ensure labour market equilibrium”) (Allan et al, 2006, p30). Importantly, the different specifications produce large differences in the estimated long-run rebound effect. The central case bargaining closure results in a total rebound effect on energy consumption of 37.0%, while fixing aggregate labour supply results in rebound falling to 32.9% and fixing the real wage results in an increase in employment of almost 1%, and a rebound effect on energy use of 51.7%. Clearly, the specification of the labour market is a crucial component in any estimate of the economy-wide rebound effect, so it is important that the relevant assumptions are clearly detailed. It is disappointing, therefore, that the studies lack transparency in this respect.

6.2.5 How increased government expenditure is recycled

Allan et al (2006) find that improvements in energy efficiency deliver a significant rebound effect which impacts on energy use but also encourages economic output and employment which in turn increase government savings. These are not recycled automatically in this model, but could be through either increased government expenditure or lower tax rates. The resulting impacts on long-run rebound were small – 36.7% when government expenditure adjusts or 41.8% when income taxes adjusted – however the differences in the economic gains were substantial. It is therefore interesting to examine how, or if, this mechanism operates in the other papers we look at.

In Grepperud and Rasmussen (2004) government expenditure is exogenous and assumed to grow at a constant rate, so we assume that there is no explicit recycling of increased revenue in this case. Hanley et al (2005) make no adjustment for this either, and neither, we understand, does Semboja (1994a). In Glomsrød and Taoyuan (2005) and Vikstrom (2004) government savings are channelled back into the economy through increasing domestic savings, and thus investment. Thus, in these two papers this recycling will have both supply-side and demand-side impacts, as explained in section 6.1.5 above. In Semboja (1994a) and Washida (2004) it is unclear how any increased government revenues are recycled. It is not apparent from Dufournaud et al (1994) we speculate that the increased household incomes reported might be due to an increased level of transfers to households.

6.2.6 The way in which the energy efficiency improvement is modelled

We must conclude this review of some of the key features of the CGE models studied, by detailing the alternative ways in which the energy efficiency improvement has been introduced to the model. It was stated that the construction of the energy composite from alternative energy types was less important in these papers since the majority introduced an energy efficiency improvement at the level of the energy composite itself. This is the case in most of the papers – Semboja (1994a), Vikstrom (2004), Washida (2004), Hanley et al (2005) and Allan et al (2006). Semboja (1994a) reports a second simulation which appears to limit the improvement in energy efficiency to the energy production sectors. The amount of energy efficiency improvement is introduced across all sectors in the same proportion in Allan et al (5%) (2006), Hanley et al (5%) (2005), Semboja (not stated) (1994a) and Washida (1%) (2004). Vikstrom (2004) introduces a 15% improvement in energy efficiency in non-energy sectors and a 12% improvement in energy sectors in a single simulation. One reviewer has commented that assuming a rate of energy efficiency in the energy sectors themselves might be inconsistent with energy production sectors currently operating close to thermodynamic limits of efficiency. We would argue that the across the board improvements in energy efficiency is the most common method for introducing this disturbance, and that the energy sectors themselves, albeit with a smaller energy efficiency improvement, might still produce significant rebound effects across the economy.

While an introduction of an energy efficiency improvement appears to be the standard method in these five papers, the three other papers studied introduce this differently. In Dufournaud et al (1994), a specific policy is modelled in which there is assumed to be significant improvements in the wood burning efficiency of stoves used by households. Glomsrød and Taoyuan (2005) examine the effects of deregulating the coal cleaning sector and allowing investment in this sector to increase, improving capital productivity in this sector and allowing the price of cleaned coal to decrease, and its supply to increase. Grepperud and Rasmussen (2004) use historical estimates of annual improvements in electricity and oil efficiency in each sector and then individually double these rates for seven

sectors. This produces four simulations in which an electricity efficiency improvement is introduced, and two in which transport oil efficiency is improved.

6.3 Conclusions on differences in key features across previous CGE studies

We summarise our discussion across these key features in Table 1. This provides a summary of each of the comments under each heading for each of the papers which have used CGE methods to analyse improvements in energy efficiency. This shows that there are very few cases where models have been constructed in a similar way. We can say that the heterogeneity which exists in CGE models generally can be seen in these eight papers. There are, for example:

- both Cobb-Douglas and CES specifications for the relevant production functions;
- four different ways in which an energy composite good has been introduced into the nesting structure;
- both infinitely inelastic and infinitely elastic specifications of the labour supply schedule, as well as two intermediate treatments,
- three methods for recycling increased government savings – namely increased investment, increased expenditure and lower taxation;
- a variety of ways in which improvements in energy efficiency has been introduced into the specification, including both attempts to model specific policy improvements (e.g. Dufournaud et al, 1994) and across-the-board improvements in energy efficiency

This diversity inhibits the systematic comparison of results.

Turning to each paper individually, we can make some comments about the clarity of the presentation and the methodological quality of the study. While a number of papers reference other papers for further details of the models they have used, we have solely examined the descriptions given in the paper. We would expect that the key features identified above would be important enough to be made clear in the exposition of each paper; hence, to the extent that they are not indicates a shortcoming in the existing literature. We provide a short summary of these issues for each paper below.

Semboja (1994a) provides a generally intuitive description both of the policy issues in Kenyan energy efficiency improvements, and simulates both an improvement in energy efficiency in production and oil fuel use. However, there is no indication of the percentage improvement in energy efficiency introduced in each simulation, making estimation of the rebound effect impossible – we can say it is greater than 100% only as it is reported that consumption of the energy composite increases by 3.5% in the first simulation and domestic energy consumption increases by 1.7% in the second simulation. This model was also rather difficult to categorise under most of our key features headings.

Table 1: CGE studies to date, critical details with each paper and estimated rebound effects

Author/Date	Country or region	Treatment of energy in production function	Elasticity of substitution with energy in production	Capital closure	Treatment of labour market	Recycling of revenue?	Energy efficiency improvements	Estimated rebound effect	Comments
Semboja, 1994a	Kenya	Type A between electricity, other fuels, capital and labour.	Cobb-Douglas at this level but Leontief between basic inputs and capital.	"Investment demand is modelled as a fixed proportion of aggregate investment, allocated to the expansion of capital stock by sector". Am awaiting a response from Dr Semboja for more details.	No discussion – am awaiting response from Dr Semboja	No recycling of any increased government revenue is apparent.	Two scenarios: an improvement of energy production efficiency and an improvement in energy use efficiency.	Greater than 100% in both cases.	Generally intuitive presentation of argument but no sensitivity analysis or notice of the improvement in energy efficiency simulated. Single energy sector also prevents analysis of differing impacts. Difficult to describe this model under our key features headings.
Dufournaud et al, 1994	Sudan	Two versions of household utility function: Energy substitutes with leisure in version 1 while energy substitutes with consumption goods composite in version 2. Production sectors do not produce or consume energy.	Two values for constant elasticity of substitution for energy employed in both versions of 0.2 and 0.4.	Sectoral capital is fixed exogenously, therefore this can be considered as a short-run model.	The aggregate wage rate is determined endogenously, and work is available at the going wage rate if households decide to work rather than have leisure time.	Government sectoral expenditure is fixed, government expenditure and saving is not. Since household incomes rise it is possible that transfers to households have increased.	Improvement in efficiency by which wood-burning stoves can meet households demand for energy from firewood. Results shown for 100%, 150% and 200% improvements in efficiency.	Household consumption of energy services increases in all cases, while demand for firewood declines. Rebound of between 47% and 77%.	Model built for answering specific question in the Sudan where policies are directed at reducing the domestic consumption of firewood. This models an efficiency improvement by which a given amount of firewood can satisfy demand for energy. Wide range of sensitivity and good explanation of the factors at work. Limited usefulness for study given no intermediate demand or production of energy, although still pronounced rebound effects evident from policy solely applying to household energy demand.
Vikstrom, 2004	Sweden	Type C in production of value added composite	Constant elasticity of substitution at sectoral level. Values range from 0.07 to 0.87.	Accumulation of capital is not explicitly treated in this model. Savings are allocated to demand for an aggregated investment good, the sectoral composition of which is allocated in line with benchmark data set.	Labour supply is fixed in the energy efficiency stage of this model.	No change in government expenditures, but government savings allocated to aggregate investment.	Single simulation with 15% increase in efficiency of use of energy of non-energy sectors, 12% increase in efficiency of use of energy in energy sectors.	50-60%	The model is simulated dynamically, with a counterfactual case in which known energy efficiency changes, factor and TFP growth, as well as structural changes are combined in turn. Results are reported here for only the energy efficiency component of these changes. There is a five year period of study, 1957-1962.
Washida, 2004	Japan	Type B in production of energy and value-added composite	Constant elasticity of substitution between energy and value added of 0.5.	Investment demand appears to be included with government expenditure. Firms demand for capital depends on cost of	There appears to be a fixed aggregate supply of labour.	Unclear what happens to increased revenues from increased economic	1% in all sectors modelled as change in efficiency factor for use of energy in production	53% in central simulation	Presentation unclear, although there is some sensitivity analysis, including varying elasticity of substitution parameter to 0.3 and 0.7 jointly with other parameters. Rebound

				capital. Aggregate capital stock appears to be fixed.		activity.			effect increases as energy/value added, labour/capital and level of energy composite substitution elasticities increase.
Grepperud and Rasmussen, 2004	Norway	Type C in production of value added composite	Constant elasticities of substitution between energy and capital at sectoral level. These differ by sectors, but generally between 0 and 1.	Model is argued to be a long-term perspective model, with mobile capital, but details are not provided in this paper.	Labour force growth is assumed in the baseline scenario, while households' decision to supply labour is based on a representative consumer with perfect foresight.	Government expenditure is exogenous and assumed to grow at a constant rate, so we assume that there is no explicit recycling of revenue in this case.	Historically estimated annual average growth rates of energy productivity at the sectoral level are doubled. Four sectors have electricity efficiency doubled, while two have oil efficiency doubled.	Oil efficiency sectors generally small rebound, while rebound, and backfire effects are seen in electricity efficiency improving sectors.	The model is simulated dynamically with a counterfactual case in which projections of world economic growth, labour force growth, technological progress and net foreign debt are assumed until 2050.
Glomsrød and Taoyuan, 2005	China	Type A in production of a value added composite	Cobb-Douglas substitution between energy, capital and labour	No capital market, but model allocates investment to sectors in fixed shares based on sectoral share of total capital in base year. Domestic saving (households and government) determines nominal investment in capital.	Exogenous real wage with entirely infinitely elastic labour supply.	Recycled through government contribution to domestic savings.	Business-as-usual dynamic scenario compared to case where costless investments generate increased investments and productivity in coal cleaning sector, lowering price and increasing supply of cleaned coal.	>100%	Coal intensive sectors benefit, as does whole economy due to high use of coal in primary energy consumption. Paper also examines cases where coal use is subject to emissions tax.
Hanley et al, 2005	Scotland	Type D in production of gross output	Constant elasticity of substitution between energy and non-energy intermediates of 0.3.	Period-by-period capital stock updating in line with difference between actual and desired capital stocks. Long run equilibrium reached when desired and actual capital stocks are equal. The interest rate is fixed in this model.	Regional bargaining labour market.	No recycling of increased government revenues from increased economic activity.	5% improvement in efficiency of energy use across all production sectors (including energy sectors).	>100% rebound or "backfire".	Interesting regional perspective where region is significant energy exporter. Efficiency improvement is region-specific, particularly improving competitiveness of energy traded goods.
Allan et al, 2006	UK	Type D in production of gross output	Same as Hanley et al.	Short-run and long-run time period results reported. Both are conceptual time periods. Capital stock is fixed in short run, while in long run capital stock is at its desired level given new values of sectoral value added, capital rental rate and wage rate. There is a fixed interest rate.	National bargaining labour market in central case simulation.	Recycling takes place in two forms - increased level of government expenditure and lower average income tax rates.	Same as Hanley et al.	37% in central case	Thorough sensitivity analysis carried out, on elasticities of substitution in production between energy and non-energy intermediates, between intermediates and value added and elasticity of export demand. Different labour market setups are explored as well as two treatments of recycling of additional taxation revenue.

Dufournaud et al (1994) build their model for answering the specific question of how changes in the efficiency with which household stoves use firewood opens up substitution possibilities for households in a CGE context. The specific focus in this paper is whether the household consumption of wood is reduced. There is a wide range of sensitivity analysis reported, both in terms of the scale of the energy efficiency improvement, the elasticity of substitution for energy and two alternative specifications of the household utility function. This study has limited usefulness for our general findings, given that there is no intermediate demand for or production of energy, but the finding of significant increases in the energy services observed is an important result.

Vikstrom (2004) uses a dynamic CGE model, similar to Grepperud and Rasmussen (2004) in this way, and also using a production function in which energy and capital form a composite with substitution possibilities with labour in value added. This paper takes known changes in energy efficiency, factor and TFP growth over the period 1957 to 1962 to decompose known macroeconomic impacts across these variables. In this review, we have focused solely on the energy efficiency improvement stage. There is a finding of significant rebound of over 50% in energy use as an input to production.

Washida (2004) is a conference paper, unlike the rest of the papers studied, and so is considerably shorter than the other papers we have examined in the course of this review. This means that there are issues which we are unable to understand from the exposition given in the paper – most notably, the precise specification of capital and labour supply. The paper does report some sensitivity analysis, varying substitution elasticities at the energy/value added, labour/capital and energy composite levels. However, the shorter details on the method employed make it difficult to make any precise quantification of the usefulness of this paper for our review.

Grepperud and Rasmussen (2004) run their CGE model dynamically against a counterfactual case in which assumptions are made about world economic growth, labour force growth, technological progress and net foreign debt. Some of the features of the model are not clear from the paper presented here, notably the specification of the capital closure, although this paper references a significant literature on the application of this model to other studies of the Norwegian economy.

Glomsrød and Taoyuan (2005) run, as explained above, an estimation of introducing a specific policy to address an issue within the economy of China which is of critical importance to the coal sector, and environmental success, of development in that country. Their finding that the coal intensive sectors benefit is certainly in part explained by the importance of coal in the Chinese economy as the primary source of energy. This paper provides a strong argument for its usefulness in this specific policy context, although it is perhaps difficult to generalise from these findings, given the uniqueness of assumptions which are made to allow the model to more plausibly describe the Chinese economy. It is difficult, for instance, to argue in a small, open economy like most of the countries of Europe or the OECD for a fully wage elastic labour supply schedule. While this means that the results cannot readily be generalised to other regions, this paper does show the value that CGE models can give to the modelling of specific policies in distinct regions. It also shows the ability of CGE models to be applied to any scale of economy.

From the most populous economy in the world, Hanley et al (2005) applied the CGE framework to investigating a small, open economy of Scotland. As with Glomsrød and Taoyuan (2005) above, this application is unique, most notably with respect to the importance of trade in energy commodities (especially electricity). Scotland is a major

exporter of energy, so the significant backfire effects experienced here can be explained in part by the improvement in the energy efficiency of the composite energy good being introduced solely in Scotland, which has a considerable impact upon the profitability of energy exports.

The model used by Hanley et al (2005) was used by Allan et al (2006), but applied to a considerably different scale of economy – the United Kingdom (some nine times greater than Scotland, and with considerably different energy trading characteristics). This paper included a large amount of sensitivity analysis, informing our selection of the key features we used to categorise the papers in this section. This sensitivity analysis included varying not only the elasticity of substitution for energy in production, but also between intermediates (including energy goods) and value added, and for export demand (Armington) elasticities. A range of labour market specifications is also explored, including both fixed labour supply and fixed real wage simulations, around a “central case” of bargained real wages. Government recycling is introduced through both increased expenditure and lower tax rates.

7 Lessons from using CGE models to analyse rebound effects

We have seen that there is considerably heterogeneity across the CGE models used to date in exploring the impacts of improvements in energy efficiency. In this section we attempt to draw out some general conclusions about what can be learned from this review. These are given under a number of headings, before in Section 8 we conclude. The headings investigated in this section are:

- What is the magnitude of measured rebound effects?
- What are the strengths and weaknesses of the CGE approach for the specific question of modelling energy efficiency improvements and rebound effects?
- What does a CGE model require to be able to model energy efficiency improvements?
- What can be said about key elasticities for the overall scale of the rebound effect?
- Production versus consumption energy efficiency?
- Costly energy efficiency improvements?

7.1 What is the magnitude of estimated rebound effects?

We have seen from our discussions of the way in which energy efficiency improvements have been introduced in the CGE models in Section 6, that there are considerable differences in the scope of the applications to date. Some models have introduced across the board stimulus to energy efficiency, while some have introduced a specific improvement in an individual sector, or combination of sectors. This will have implications for the scale of the estimated rebound effects that these papers report.

In Section 5 it was argued that zero rebound would be implausible from a theoretical viewpoint – such a case requires that not only does energy combine with other inputs through Leontief technology, but also that the demand for energy is entirely invariant with respect to own price and that relevant goods' demands be completely unresponsive to price changes, or that energy's share in the relevant composite be approximately zero. Similarly, the argument that backfire was theoretically impossible was ruled out, in favour of the question of the magnitude of measured rebound effects being an empirical issue, dependent on the specific economy, and context, in which the question is posed.

The empirical results reported in Table 1 show that both rebound (Vikstrom, 2004; Washida, 2004; Grepperud and Rasmussen, 2004; Allan et al, 2006) and backfire (Semboja, 1994a; Hanley et al, 2006; Glomsrød and Taoyuan, 2005) have been found in studies to date. We can draw tentative conclusions between the backfire results and the initial position of the economy in question as an open economy with trade in energy. Semboja (1994a) and Hanley et al (2006) both examine countries in which energy is an important export and import commodity. An improvement in the efficiency by which energy is used in production in such an economy will have potentially significant effects to the domestic energy sectors. In the case of Scotland, the energy efficiency improvement in production across all sectors of the economy stimulates the demand for energy (primarily electricity) exports to the rest of the UK (Scotland is, in the initial SAM, a significant exporter of energy to the rest of the UK).

In terms of rebound, Greening et al (2000) in their survey of empirical studies noted that most of the studies up to that point had been generally confined to estimating the direct rebound effects (omitting what they termed the "indirect" and "economy-wide" effects). The

literature they found predicted direct rebound of the order of 30% on average. In all of the CGE studies examined above this figure is exceeded, with a minimum rebound of 37% (Allan et al, 2006).

7.2 Strengths and weaknesses of the CGE approach for modelling rebound effect

What are the major strengths and weaknesses of the CGE approach for this type of problem? First, from a conceptual point of view, a major strength of CGE analysis is that it is grounded in standard economic theory, but can deal with circumstances that are too complex for tractable analytical solutions. As such, CGE analysis is a numerical aid to analytical thought. For example, in the energy efficiency case we know there are a whole range of substitution, income, output and sectoral composition effects that will operate simultaneously. A CGE analysis can deal with this simultaneity. Thus, Greening et al's (2000) acknowledgement that "prices in an economy will undergo numerous, and complex, adjustments. Only a general equilibrium analysis can predict the ultimate impact of these changes" (p397).

A second advantage is that formal theoretical analysis can often indicate the direction in which a variable will move after the introduction of an exogenous disturbance, but is unable to quantify the size of the change. For example, we can say from a fairly informal theoretical analysis that we would expect an energy efficiency improvement to be accompanied by rebound effects. However, there is a crucial difference, for the viability of policy, between a 5% rebound and 150% rebound. CGE analysis is parameterised to reflect the structural and behavioural characteristics of the economy under analysis. Whilst the CGE simulation would not claim pinpoint accuracy, an appropriate order of magnitude is achievable. The causal processes at work in a CGE, such as substitution and output effects, allow in theory the measured rebound effect to be decomposed into the constituent components. Furthermore, a sensitivity analysis is feasible, but is not always conducted in practice. Such sensitivity analysis might also be used to quantify the rebound effect from introducing a policy in a specific sector, allowing policy to be targeted most appropriately.

Third, from a modelling perspective, CGE analysis has a very well developed supply side. Many policy issues, of which energy efficiency is one, are essentially supply side problems. However, it is common to see analysts attempting to tackle such problems with demand driven models. As we have only considered CGE model this is not the case in any of the empirical studies outlined above, where all acknowledge the supply-side impacts of such improvements in energy efficiency. Typical demand-driven models, such as standard Input-Output, would not be able to model the impacts of policies targeted at the supply-side.

Fourth, from a purely practical point of view, CGE modelling makes it simpler to evaluate the net impacts of energy policy change since it makes very clear what the "counter-factual" is. This counter-factual is the base-line run of the model without the change in energy efficiency. All changes in output, employment and energy use that are observed from the technology shock are then measured relative to this baseline. This makes the marginal effects of technology change clear. However, evaluating the same policy using time series or cross-sectional statistical data requires us to be able to identify the counter-factual by appropriate statistical control. This may be much harder, and risks confusing the actual drivers of changes in energy use. In Grepperud and Rasmussen (2004) and Glomsrød and Taojuan (2005) the counterfactual was a baseline scenario with assumed growth rates for key macroeconomic variables, while in Allan et al (2006), Hanley et al (2006) and Washida

(2004, 2006) a reference constant base is compared against the subsequent results with the policy disturbance "switched on".

To turn to the weaknesses of this approach, the first is that a CGE model is information-intensive in that it requires an initial set of multi-sectoral accounts (in the form of a SAM) and a large number of parameter values. As has been discussed above, many of these parameters will not be estimated econometrically, or at least not for the economy under consideration or for that time period. Moreover, CGE simulation models are rarely tested against their predictive power. It is therefore very easy to invest the model results with misplaced concreteness. Again, this is where extensive sensitivity analysis would reveal the robustness of any central estimate to a range of plausible assumptions about key behavioural variables.

Second, some would see the theoretical supply-side rigour of the model as a weakness. For example, CGE models typically take it as axiomatic that firms maximize profits, which implies that they minimise costs. However in the specific case of energy efficiency, there is a significant and growing literature that focuses on barriers to the adoption of the most efficient energy technologies (Sorrell et al, 2004). This literature argues that conventional neoclassical behavioural functions of the type assumed here fail to capture some of the significant barriers to the penetration of new technologies. Such barriers include, for example, imperfect information and significant transaction costs that are neglected in the optimisation processes that underlies the functions. Although adjustment costs can be incorporated into CGE models, such models might still privilege market forces as against behavioural ones.

Third, as we saw in Table 1 and Section 6, there exists considerable variation between CGE models so that care needs to be taken when comparing results across models. In particular, there are a number of issues about closing the model where different assumptions can be made. These are likely to apply to the way in which the labour and capital markets are assumed to operate. We have seen in the papers described above how changing some assumptions can generate very different simulated outcomes. Sometimes model results can be driven by assumptions that are not apparent to a reader not acquainted with the model.

Where one is dealing with economic issues - such as the impact of energy efficiency improvements - which have complex system wide impacts, CGE analysis should be one of the methods adopted. CGE analysis should be used both as a numerical aid to analytical thought, but also as a tool to assess broad orders of magnitude for different effects. However, these models should be used in an open manner. Their strong theoretical basis means that unlike many econometric models, they are not black boxes, but should produce results that are both clear and comprehensible. This "black box" argument is a common criticism against CGE models, and relates to the viewpoint that the causality between assumptions entering the CGE model and output produced by the model being opaque from the reader, and apparent only to those who have designed the model. It is a common complaint of CGEs that they are black boxes, a feeling that can be overcome through modelers explaining the results with the help of economic theory. We saw in Section 6 that, while some information on our key features is not apparent for a small number of papers, all of the papers studied have attempted to argue the model results from economic theory, some with more success than others.

7.3 What does a CGE model require to model energy efficiency improvements?

As we have said above, it is not that a CGE framework is required to model energy efficiency improvements, or that it is required for there to be rebound, or backfire, effects in terms of increased energy use. Rather, CGE can be an appropriate tool to use when attempting to measure the aggregate, and sectoral, impacts across an economy of a policy which, by its very nature, is designed to have impacts that are considerable and will differ across sectors with different energy intensities and other characteristics. As we have discussed in Section 3, a key feature of all CGE models is their flexibility, allowing coherent formulation of the supply-side of an economy in line with economic theory and, in the papers we have examined in Section 6, based on specific countries or regions. As a policy which impacts upon the characteristics of factor supplies, expanding the range of production possibilities for a given factor availability, this flexibility is valuable when modelling the resulting system-wide impacts.

7.4 What can be said about key elasticities for the overall scale of rebound effect?

As has been argued above the overall scale of the rebound effect in any economy is an empirical issue, specific to the economy and policy under examination. It is difficult to say *ex ante* which elasticities will be the most important in terms of driving the overall scale of the rebound effect. Some guidance on this point can be learned from economic theory (e.g. Hicks on industrial demand). Most of the existing CGE papers we have reviewed have focused on the elasticity of substitution between energy and other inputs and only a subset of these have conducted systematic sensitivity analyses of elasticities of substitution,. Allan et al. (2006) have also studied elasticities of export demand and shown them to be a potentially important driver of results. Howarth (1997) and Saunders (1992, 2000) rightly stress the importance of the elasticity of substitution of energy (or energy services) for other inputs in determining the size of rebound effects. However, within a general equilibrium context, other characteristics such as the openness of the economy, the elasticity of supply of other inputs (capital and labour), the energy intensity of individual production sectors and final demands, the elasticity of substitution between commodities in consumption and the income elasticity of demand for commodities are also potentially important.

Clearly, informed sensitivity analysis can be used to illuminate the important parameters for the scale of the rebound effect. Informed analysis can identify the elasticities which might be important, and sensitivity analysis can reveal the extent to which these are important for measured results. "Comprehensive" sensitivity testing, where all assumed parameters are varied, is less imperative and may also be impractical given the time necessary for constructing, running and explaining alternative simulation results. Informed sensitivity analysis, on the other hand, should be regarded as an important part of any CGE analysis. It can be seen that some sensitivity analysis is generally performed in the studies reviewed in Section 6, although this is generally less than might be desirable.

7.5 Production vs. consumption energy efficiency

We have seen in Section 6.2.6 that we might consider that the "normal" way for energy efficiency improvements to be modelled is through improving the energy efficiency of production sectors. There appears, from this literature, to be little that can be said about the economy-wide rebound effects of changes in energy efficiency in consumption activities, such as households. Sorrell and Dimitropoulos (2005) note that there is "considerably more"

evidence for rebound effects resulting from energy efficiency improvements by consumers than by producers, and that these effects differ across different types of consumption activities (e.g. transport and heating) and income groups. However, the majority of this evidence relates to direct rebound effects and not to indirect or economy-wide effects. Where there are differences across household income groups, this would require a greater degree of disaggregation to be introduced on the demand side of the CGE models than is generally the case. Detail on different consumption components, such as household disaggregation, is currently missing from the studies reported in Section 6 and this could be an important area for future research.

7.6 Costly energy efficiency improvements

It has been argued that in simulating energy efficiency improvements, modellers have often assumed that such improvements can be made costlessly by a firm. A considerable literature has shown that there can be a whole series of barriers to the introduction of more efficient technologies and techniques (Sorrell et al, 2004). In terms of the CGE modelling experience, while most studies have introduced energy efficiency improvements without additional costs in other areas, some (Allan et al, 2006 and Glomsrød and Taojuan, 2005) have considered how these additional costs might be treated within a CGE framework. Allan et al (2006) introduce a cost to the efficiency of labour inputs in production, which intends to represent the "additional costs to labour of implementing the improvement in energy efficiency" (p47). The results from this simulation show that there is less rebound under this scenario than one without costs, in part since the gains to employment realised in the case without costs are reduced when labour efficiency is reduced.

Clearly, the way in which the additional costs of making energy efficiency improvements are modelled will affect the estimated size of rebound effects. It might be important therefore, that attempts are made to quantify the mechanisms through which energy efficiency improvements could be made, and the additional costs that identifying and making such improvements would have on the sector or economy in question. It need not be the case that introducing a cost to energy efficiency improvements reduces the scale of the rebound effect, but will depend on how the cost might be introduced elsewhere in the system.

8 Conclusions and priorities for further research

What can be concluded from this review of CGE models and their application to rebound effects? CGE models have been and will continue to be used to examine the way in which energy efficiency improvements impact across an economy. These models can shed light on the resulting impacts on energy use from the stimulus to energy efficiency, in a manner that is consistent with economic theory, and internally tractable – allowing the results to be interpreted intuitively. Perhaps with appropriate use, a carefully constructed CGE can overcome this “black box” criticism often levelled at CGE practitioners. Careful sensitivity analysis, with respect to closures and functional forms as well as parameter values, can help reveal the source of any modelling surprises. Such results can be shown across sectors, a crucial importance where the sectoral impacts can be important for distributional reasons. The estimated effects of energy efficiency improvements are clearly sizeable, both on the economy and on energy use.

Rebound effects range from 37% to backfire, indicating that there is no empirical CGE support for the zero rebound case – where energy use falls by the full amount of the improvement in energy efficiency – and that backfire (rebound over 100%) cannot be ruled out empirically.

It should be noted that there is an acceptance in the reviewed literature that the existence of rebound or backfire does not mean that energy efficiency policies should be abandoned: instead, they should not be considered in isolation. Dufournaud et al (1994), argue that “energy efficiency policies lead to other gains, especially income gains”, while Allan et al (2006) argue that the energy efficiency policies should be considered alongside other policies, such as energy taxation, to perhaps realise the potential for win-win economic and environmental benefits.

Future research might be focused on several key areas. Firstly, there is a lack of CGE research into the impacts that energy efficiency improvement have. Given the environmental, economic and energy benefits which are commonly expected from such improvements, it is surprising that there has not been more research into the system wide impacts. Secondly, regular updates of the key elasticities within the CGE model, and applications at the geographic levels of which there are CGE models, will ensure that the researcher is able to use the most robust parameter estimates in simulations. Key elasticities have been shown to be important for the measured impact of the rebound effect in most cases, as would be expected. Further, sensitivity analysis to the assumptions used should be reported, identifying the full range of results for plausible model closures and highlighting the importance of specific assumptions about the economy under investigation. This would help to show how robust the central results are, and with what confidence they can be expressed.

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