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THE ADDED VALUE FROM A GENERAL EQUILIBRIUM ANALYSES OF INCREASED EFFICIENCY IN HOUSEHOLD ENERGY USE

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The added value from a general equilibrium analyses of increased efficiency in household energy use

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Value-added from a general equilibrium analyses of increased efficiency in household energy use

Abstract

The aim of the paper is to identify the added value from using general equilibrium techniques to consider the economy-wide impacts of increased efficiency in household energy use. We take as an illustrative case study the effect of a 5% improvement in household energy efficiency on the UK economy. This impact is measured through simulations that use models that have increasing degrees of endogeneity but are calibrated on a common data set. That is to say, we calculate rebound effects for models that progress from the most basic partial equilibrium approach to a fully specified general equilibrium treatment. The size of the rebound effect on total energy use depends upon: the elasticity of substitution of energy in household consumption; the energy intensity of the different elements of household consumption demand; and the impact of changes in income, economic activity and relative prices. A general equilibrium model is required to capture these final three impacts.

Keywords: Energy efficiency; indirect rebound effects; economy-wide rebound effects; household energy consumption; CGE models.

JEL codes: C68, D57, D58, Q41, Q43, Q48

1. Introduction

Economy-wide rebound effects resulting from energy efficiency improvements in production have been extensively investigated. This analysis has often used a computable general equilibrium (CGE) modelling framework (see Dimitropoulos, 2007; Sorrel, 2007; and Turner 2013 for a review). However, very few studies attempt to measure the economy-wide impacts of increased energy efficiency in the household sector. Following the work of Khazzoom (1980, 1987) there have been a numbers of partial equilibrium studies (Dubin *et al.* 1986; Frondel *et al.* 2008; Greene *et al*. 1999; Klein, 1985 and 1987; Nadel, 1993; Schwartz and Taylor, 1995; West, 2004). Further, Greening *et al*. (2000) gives a detailed and extensive summary of the extent of rebound on household consumption for several types of energy services. This literature assumes that there are no changes in prices or nominal incomes following the efficiency improvement and that impacts are limited to the direct market for household energy use. This approach permits consideration of the direct rebound effect only.

To our knowledge, Dufournaud *et al*. (1994) is the only study that investigates economy-wide rebound effects from increased energy efficiency in the household sector. It examines the impacts of increasing efficiency in domestic wood stoves in Sudan. Druckman *et al*. (2011) and Freire-Gonzalez (2011) use a fixed price input-output model to consider indirect rebound effects resulting from household income freed up by energy efficiency improvements and spent on non-energy commodities. However, we consider their work an extension of partial equilibrium analysis in that they fail to consider endogenous prices, incomes or factor supply effects.

The aim of the present paper is to identify the added value from using general equilibrium techniques to consider the economy-wide impacts of increased efficiency in household energy use. We take as an illustrative case study the impact of a 5% improvement in household energy efficiency. This impact is measured through simulations that use models that have increasing degrees of endogeneity but are calibrated on a common UK data set. That is to say, we calculate rebound effects for models that progress from the most basic partial equilibrium approach to a fully specified general equilibrium treatment.

The reminder of the paper is structured as follows. In Section 2 we define rebound effects in household and total energy use and show how these are calculated. In Section 3 we estimate a key parameter in the determination of the rebound effect, the elasticity of substitution between energy and non-energy commodities in household consumption. Section 4 considers the partial equilibrium household and total energy use rebound values and investigates the relationship between the two. Section 5 introduces the AMOS computable general equilibrium modelling framework. In Section 6, this model is used in general equilibrium rebound simulations. In Section 7 we comment on the range of rebound values and identify the value-added from adopting a general equilibrium approach and Section 8 is a short conclusion.

2 Rebound Effects

To begin, it is useful to specify what we mean by an increase in energy efficiency. We categorise an increase in household energy efficiency as being a change in household “technology” such that the energy services per unit of physical energy is increased. An alternative way of expressing this is that the energy value in efficiency units has risen.[1] This implies that the original level of household utility can be achieved through the consumption of

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[1] We discuss in Section 3 the mechanisms whereby such efficiency improvements might come about.

the original levels of other household goods and services, but a lower input of energy consumption.[2]

We define the rebound effect generated by an increase in energy efficiency as a measure of the difference between the proportionate change in the actual energy use and the proportionate change in energy efficiency. This difference is primarily driven by the fact that, *ceteris paribus*, an increase in the efficiency in a particular energy use reduces the price of energy in that use, measured in efficiency units. This reduction then leads consumers to substitute energy, in efficiency units, for other goods and services.

This distinction between energy quantity and price measured in natural and efficiency units is important in explaining how the rebound effect operates. However, in the present paper, unless we explicitly state otherwise energy is being measured in natural units. The fall in the price of energy, measured in efficiency units, implies that proportionate change in energy use is typically less than the proportionate change in energy efficiency. This is the rebound effect. Moreover, in principle, energy use can actually rise in response to an improvement in energy efficiency, if its use is sufficiently price sensitive. This is known as backfire (Khazzoom, 1980 and 1987).

In this paper we investigate the impact of an improvement in the efficiency of energy use in household consumption. In this case, for a proportionate improvement in household energy use of γ, rebound in the household consumption of energy, R_C, is measured as:

$$R_C = \left[1 + \frac{\dot{E}_C}{\gamma}\right] \cdot 100 \tag{1}$$

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[2] We do not categorise a reduction an improvement in energy efficiency in household consumption as simply a reduction in the direct energy intensity of consumption. For example, we do not count a reduction in energy use by households generated by an increase in the price of energy (through a carbon tax, for example) as an improvement in household energy efficiency.

where $\dot{E}_C$ is the proportionate change in energy use in household consumption.

In interpreting equation (1) it is important to be mindful of the sign of the proportionate change in energy use, $\dot{E}_C$. If in the case we consider, the 5% efficiency improvement leads to a corresponding 5% reduction in energy use in consumption, the rebound value R_C would be zero; there would be no rebound. However, if the fall in energy use were less than 5%, then there would be a positive rebound, which increases as the reduction in energy use takes smaller absolute values. Rebound is 100% if the use of energy is unaffected by the increased efficiency: if the impact on energy use is positive, then rebound is greater than 100% and this is known as backfire.

We are also interested to the economy-wide rebound within the target economy[3] of household energy efficiency improvements on total energy use; that is to say, energy used both in consumption and production. The total rebound formulation used in this case, R_T, is given as:

$$R_T = \left[1 + \frac{\dot{E}_T}{\alpha\gamma}\right] \cdot 100 \qquad (2)$$

where α is the initial share of household energy consumption in total energy use. The term $\frac{\dot{E}_T}{\alpha\gamma}$ can be expressed as:

$$\frac{\dot{E}_T}{\alpha\gamma} = \frac{\Delta E_T}{\gamma E_C} = \frac{\Delta E_C + \Delta E_P}{\gamma E_C} = \frac{\dot{E}_C}{\gamma} + \frac{\Delta E_P}{\gamma E_C} \qquad (3)$$

where Δ represents absolute change and the P subscript indicates production. Substituting equation (3) into equation (2) and using equation (1) gives:

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[3] Our interest here is limited to the macro level rebound effect within the target economy. That is to say we are abstracting for potential spillover effects to other countries/regions.

$$R_T = R_C + \frac{\Delta E_P}{\gamma E_C} \cdot 100 \qquad (4)$$

This shows that the total rebound will be greater than the consumption rebound if the energy use in production increases as a result of increases in efficiency in energy use in consumption. If, on the other hand, energy use falls in production, total rebound is lower than consumption rebound.

3. Data and elasticity of substitution of energy use in consumption

In this paper we identify the additional precision achieved through moving from a partial to a general equilibrium analysis of the rebound effects. We consider the specific case of energy efficiency improvements in household consumption. [4] We quantify the rebound effect through simulation using a given data set which provides common structural characteristics across all the models. Specifically we use a specially constructed UK symmetric industry-by-industry Input-Output table based on the published 2004 UK Supply and Use Tables.[5] Import data in input-output format were provided by colleagues at the Stockholm Environment Institute. The input-output accounts are aggregated to identify 21 economic activities (commodities/sectors). Table 1 gives the sectoral disaggregation, separately identifying four energy sectors; coal, oil, gas and electricity.

In Table 2, we report the energy input requirement for each of the production sectors and the energy-output multiplier effects expressed in monetary terms. That is to say, for each sector we measure the direct and indirect increase in the value of output in energy industries

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[4] We are increasing energy efficiency in all energy use: coal, oil, gas and electricity.

[5] See http://www.strath.ac.uk/fraser/research/2004ukindustry-byindustryanalyticalinput-outputtables/ for details.

generated by a unit increase in the final demand for that sector. The energy requirements are represented by the appropriate direct input-output coefficients (the A matrix) while the energy-output multipliers correspond to the Type I Leontief inverse, $[1\text{-}A]^{-1}$. To calibrate the Computable General Equilibrium model, the conventional Input-Output accounts are augmented with all other transfer payments to form the 2004 UK Social Accounting Matrix.[6] In all the analysis we have a single initial vector of household consumption given in UK 2004 Input-Output accounts.

A key parameter that drives rebound analysis is the elasticity of substitution between aggregate energy and non-energy goods and services in the household's utility function. In each of the models we use, household utility, *C*, in any period is given by:

$$C = \left[\delta^{E} \gamma E_{C}^{\frac{\varepsilon-1}{\varepsilon}} + (1-\delta^{E}) NE_{C}^{\frac{\varepsilon-1}{\varepsilon}} \right]^{-\frac{\varepsilon}{\varepsilon-1}} \qquad (5)$$

Where, NE_C is the consumption of non-energy commodities, ε is the elasticity of substitution between energy and non-energy commodities in consumption and $\delta^{E} \in (0,1)$ is the share parameter.

We estimate the value of the elasticity of substitution using UK household consumption data from 1989 to 2008.[7] Details about the estimation procedure are reported in Appendix 1 and Lecca *et al* (2011a). As expected, consumer demand is more sensitive to prices over the long run than the short run: the short- and long-run elasticities of substitution are estimated as 0.35 and 0.61 respectively. The estimation uses the conventional generalized maximum entropy

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[6] For more information on Input-Output accounts and Social Accounting Matrices see Miller and Blaire (2009).

[7] The value of the elasticity of substitution is likely to vary across types of energy services (such as personal transportation, residential space heating, etc.). However, at this stage for pedagogic reasons we impose a common value across all household consumption energy uses.

(GME) method (Golan *et al.* 1996). This is a widely used technique for generating parameter estimates for CGE models, though for comparative purposes OLS estimates are also reported in the Appendix 1. Our estimated elasticity values are broadly in line with previous empirical evidence for the UK households (e.g. Baker and Blundell, 1991 and Baker *et al*. 1989).

We have estimated the substitution elasticities by observing the reaction of household energy consumption to changes in energy price. However, the question arises as to whether the same substitution elasticities are appropriate for changes in the use of energy where efficiency improvements have reduced the price of energy, measured in efficiency units? The answer might lie in the nature of the efficiency improvement. We see no reason not to use the long-run elasticity of substitution where long-run simulations are performed. However, for short-run simulations we will argue that it in some circumstances might be appropriate to use the long-run elasticity value.

The short-run adjustment in household consumption of energy in response to a change in energy prices might be lower than the long-run value for two different reasons. First, there might be a degree of inertia in the consumption response: it might take time before the consumer is aware that the energy price has changed and he or she might exhibit a degree of lethargy in making the appropriate adjustment in consumption. However, a second reason might be that a full adjustment to the new energy price requires an investment in consumer durable goods, which only occurs in the long run.

For example, imagine that the price of gasoline falls. In the short run consumers will make more and longer trips in their existing cars. However, in the long run, when a new car is purchased, consumers might also increase the engine capacity, and therefore fuel consumption. In this case the greater adjustment of energy use in the long run is explained by the need to make complementary adjustments in consumer durables to fully exploit the change in price.

These arguments are relevant for analysing the impact of an improvement in household energy efficiency. If energy efficency is not embodied in capital equipment, it should operate in a way analogous to a price change. For example, imagine that chemical additives to gasolene increases the miles per gallon achieved by all cars by the same proportionate extent. In this case we should use the different short- and long-run elasticities for analysing the corresponding time periods. That is to say, the short-run adjustment should have motorists more frequently and extensively using their cars, whilst a fuller adjustment is possible in the long run where the type of car, size of engine etc. might change as a result of lower effective gasolene costs.

However, if the energy efficiency improvement is embeddded in the design of a consumer durable, then the efficiency improvement is not experienced untill the consumer purchases a new vintage. For example, the improvement in energy efficiency might be delivered through a new car engine design. This implies that the efficiency increase is not experienced untill the new engine is purchased. However, it is likely that this will be coincident with decisions taken over the size of the car, car engine etc. Therefore these are decisions where the long-run value of the elasticity of substitution is relevant. This is so even in the short run, where the rest of the economy has not fully adjusted to the implied price and income changes flowing from the energy efficiency improvement.

4. A partial equilibrium framework

In the partial equilibrium analysis applied here, we assume that the prices of all commodities and services, including energy prices, are fixed and that there is no change in household nominal income. This is the impact that would be appropriate for analysing the decision by a single household to introduce improvements in energy efficiency. However, although we focus on an improvement in energy efficiency in consumption, we are also interested in the subsequent impact on energy use in production too. This can be achieved, in this case, whilst still maintaining the partial equilibrium assumptions of fixed prices and household income, through the application of conventional Type I Input-Output analysis.

4.1 Household energy use

To determine the level of rebound in household energy use, first we need to derive the elasticity of demand, η, from the elasticity of substitution, ε. This is given as (Gørtz, 1977):

$$\eta = \varepsilon - (\varepsilon - 1)\lambda \tag{6}$$

where λ is the share of energy in household expenditure. From the UK 2004 Input Output accounts, 3% of household consumption is spent on energy so that $\lambda = 0.03$. In Section 3 we report the values for the short- and long-run elasticities of substitution as 0.35 and 0.61 respectively. Therefore from equation (6), the short- and long-run energy price elasticities of demand are given as 0.369 and 0.622.

With no change in the price of energy, a proportionate increase in efficiency in household energy consumption, γ, generates an equal proportionate reduction in the price of energy to consumers, measured in efficiency units. If the elasticity of demand for energy is η, where η takes a positive sign, the proportionate change in consumer energy demand, again measured in efficiency units, $\dot{E}_C^F$, is given as:

$$\dot{E}_C^F = \gamma\eta \tag{7}$$

The proportionate change in consumer energy use, measured in natural units, is the proportionate change in efficiency units, minus the change in efficiency:

$$\dot{E}_C = \eta\gamma - \gamma = (\eta - 1)\gamma$$	(8)

where $\eta \geq 0$ and $\frac{\partial \dot{E}_C}{\partial \eta} = \gamma > 0$. If energy demand is completely price inelastic, so that $\eta = 0$, household energy use falls by the full proportionate amount, γ. On the other hand where price elasticity equals one, energy use is unchanged. If demand is price elastic, so that $\eta > 1$, household energy use increases as a result of improvements in household energy efficiency.

Substituting expressions (6) and (8) into equation (1) produces:

$$R_C = 100\eta = 100(\varepsilon - (\varepsilon - 1)\lambda)$$	(9)

Using the short- and long-run demand elasticities produces the short- and long-run rebound values of 36.9% and 62.2%.[8] These values are entered in the top row of Table 3.

Equation (9) calculates what is conventionally known as the direct rebound. These figures lie within the range of available US and European estimates for specific household energy uses (see e.g. Greening et al., 2000 and Freire-Gonzales, 2010). A comprehensive review of empirical estimates of direct rebound effects is provided by Sorrell *et al*. (2009).

4.2 Total energy use

In the analysis reported in Section 4.1, the improvement in energy efficiency operates in a manner that is observationally equivalent to a change in the representative household's tastes, with fixed nominal income and prices. That is to say, the improvement in energy efficiency is

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[8] We consider the estimated elasticity of energy demand as a proxy of the direct rebound effects (Khazzoom, 1980). This is the easiest and more straightforward definition of direct rebound, though it has been criticized by Sorrell and Dimitropoulos (2008) as subject to bias.

reflected solely in consumption shifting.[9] With rebound values less than 100%, as reported here, this implies a fall in consumption expenditure on energy and an increase in the expenditure on all other goods and services.[10]

We can retain the partial equilibrium assumptions of fixed prices and household income but incorporate the impact on total energy use by adopting a Type I Input-Output analysis (Miller and Blair, 2009). In this approach, the impact on energy use in both household consumption and industrial production is identified and the relevant total rebound measure, as expressed in equation (2), can be calculated. This captures the notion of energy being embodied in consumption goods or services, in the form of the energy required, directly or indirectly, in the production of these goods and services (Miller and Blaire, 2009, and Sorrel, 2009).

We introduce a shock in the Input-Output system by reducing household final consumption expenditure on (both UK and imported) energy (coal, oil, gas and electricity) to reflect the reduced energy requirement when efficiency in household energy use rises in line with the analysis in the previous section. We simultaneously increase household spending on other (non-energy) goods and services, using the distribution of initial expenditure on (domestic and imported) non-energy goods and services. This distribution is given in the Input-Output accounts. This method shares some characteristics with Freire-Gonzalez (2011): it extends Druckman *et al.* (2011) by incorporating the impact on indirect rebound from the reduction in energy use embodied in the reduction in energy supply itself.

The change in household consumption expenditure on energy, ΔE_C, is matched by an equal and opposite change in non-energy household expenditure, ΔNE_C, and is given as:

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[9] An increase in energy efficiency with fixed prices and nominal income does mean that household utility will rise. The implications of this are dealt with in more detail in Section 6.2.

[10] However, if backfire occurs, so that rebound is greater than 100%, household expenditure on energy will rise and the expenditure on other goods and services fall.

$$\Delta E_C = -\Delta NE_C = X_T \left(\frac{R_C}{100} - 1 \right) \lambda \gamma \tag{10}$$

where X_T is total household expenditure. Using Type I Input-Output multipliers, the change in total energy use, ΔE_T, equals:

$$\Delta E_T = \Delta E_C (1 + m_E^E) + \Delta NE_C m_N^E \tag{11}$$

where m_E^E and m_N^E are respectively the amounts of energy used, directly or indirectly, in the production of one unit of energy and one unit of non-energy household consumption. Household energy use can be expressed either as the share, λ, of the total household expenditure or a share, α, of the total energy use. Using this result produces:

$$E_T = \frac{\lambda X}{\alpha} \tag{12}$$

Using equations (10), (11) and (12) produces:

$$\dot{E}_T = \alpha \gamma \left(\frac{R_C}{100} - 1 \right) (1 + m_E^E - m_N^E) \tag{13}$$

Using the notation $\Delta m^E = m_E^E - m_N^E$ and substituting equation (13) into equation (2) gives:

$$R_T = R_C + (R_C - 100) \Delta m^E \tag{14}$$

Equation (14) expresses the total partial equilibrium rebound as a function of the rebound value in the household consumption of energy, R_C, and the difference between the embodied energy in the production of energy and non-energy goods and services, Δm^E. We expect the production of energy to be relatively energy intensive, so that $m_E^E > m_N^E$, and therefore *that* $\Delta m^E > 0$: this is certainly the case with the UK Input-Output accounts. Combined with equation (14), this implies that the relationship between the partial equilibrium household consumption rebound and total rebound is represented in Figure 2.[11]

Consider first the situation where the household consumption rebound is 100%. This means that there is no change in the household use of energy as a result of the efficiency improvement. There is therefore similarly no change in production: $R_T = R_C = 100\%$. If household consumption rebound is greater than 100%, so that backfire occurs in household consumption of energy, then consumers spend a greater share of their income on energy after the efficiency improvement. Because the production of energy is relatively energy intensive, this means that the energy used in production increases and the total rebound value will be greater than the household rebound: $R_T > R_C$. On the other hand, if rebound is less than 100%, household consumption switches to non-energy commodities. This implies that the total energy use rebound will be less than the household consumption rebound, as energy use in production falls. If $R_C < \left[\dfrac{\Delta m^E}{1+\Delta m^E}\right]100$, then the total rebound is actually negative. That is to say, the proportionate reduction in total energy use, measured as a percentage of the initial household energy use, is greater than the efficiency improvement. Where the household consumption rebound is zero, the total rebound equals $-100\Delta m^E$.

We can quantify the partial equilibrium total rebound generated by the consumption expenditure shifting associated with the improvement in household energy efficiency. For the 36.90% household consumption rebound value estimated using the short-run elasticity of substitution, the proportionate reduction in household consumer expenditure on energy, $\dot{E}_C$, equals 3.16%. Where $\gamma = 5\%$ and $\alpha = 0.344$, this corresponds to a 109355 TJ reduction in

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[11] In equation (14) the rebound effect incorporates all of the indirect effects, negative and positive. For an alternative approach see Guerra and Sancho (2010), where the embodied energy requirement of the energy supply sector is included as part of the potential energy savings.

household energy use and to a £752.57 million reallocation in UK household consumption across the seventeen non-energy consumption sectors, in line with the initial distribution of expenditure (domestic and imported) in those sectors. The result is a fall in total energy demand of £1002 (137363 TJ) which corresponds to 1.44% of total UK energy use (across households and producers), so that $\dot{E}_T = -1.44\%$. This produces a total rebound value (R_T) of 15.96%. Given that the household consumption rebound (R_C) is positive, at 36.9%, the indirect component of the rebound effect is negative with a value of 20.94%. [12]

Given that energy is disaggregated into four separate sectors in the Input-Output accounts, we can calculate a separate total rebound value for each energy type. In this simulation, we impose the same energy efficiency improvement across all energy sectors and the same household consumption demand elasticity. Therefore all the energy sectors will have the same short-run household consumption rebound value of 36.9%. However, the total rebound effects vary dramatically.

The value for the total rebound for coal is negative, at -53.49%. As a result of the 5% improvement in efficiency in the use of all energy types in household consumption, the total demand for coal will fall by 1.01%. The classic rebound effect limits the improvement in energy efficiency: however in this case the efficiency impact is magnified. This is because the use of coal in household consumption is low, but its use as an intermediate input into energy (primarily electricity) production is high. Therefore the positive rebound effects in household consumption are swamped by negative rebound effects from the reduced demand for coal in production, particularly as electricity output falls.

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[12] From the figures given in Table 3 the value of the differential intermediate energy multiplier, Δm^E, as used in equation (14) is 0.33.

For the other three energy sectors (gas, electricity and oil), the total short-run rebound values are all positive, with values of 18.30%, 3.81% and 36.01% respectively. The rebound value for electricity is below, and the values for gas and oil are above, the value for the combined energy sector.

Where the estimated long-run demand elasticity is used in the rebound calculations, there is a larger household consumption rebound value. This implies a smaller reallocation of household expenditure in favour of non-energy goods and services. In this case, $\dot{E}_C$ indicates a 0.87% fall in expenditure on energy, a reduction of 65509 TJ which equates to £450.9 million to be reallocated to non-energy household consumption. The total energy rebound, R_T, is 49.66%, with the impact of indirect expenditures (R_T-R_C) being to reduce the rebound by 12.54 percentage points. The rebound effect for the four individual energy sectors is now positive for all energy-types: 8.05% for coal, 51.06% for gas, 42.38% for electricity and 61.67% for oil. The ranking of the sectors remains the same, both relative to each other and also with the combined energy use value. Specifically, the total rebound values for gas and oil use are slightly higher than the combined energy household consumption values, electricity and coal are lower.

Generally, there is an expectation that the total rebound will be bigger than the household consumption value. However, this will not typically be the case. Energy production is usually more (directly and indirectly) energy-intensive than non-energy production. If rebound is less than 100%, the reallocation of the budget reduces the household expenditure on energy and increases it on non-energy commodities and services. In this case, the indirect component of the rebound will be negative, so putting downward pressure on the total rebound value.

5. General equilibrium rebound effects – endogenous prices and incomes

The analysis in Section 4 holds prices and nominal household income fixed. However, as the demand for goods and services varies, if there are any constraints on supply, prices will also change. This will affect sectoral revenues, the returns to factors of production and also household incomes. In the analysis in this section we allow prices and incomes to vary in determining the rebound effect. These effects are captured through the use of Computable General Equilibrium (CGE) modelling.

5.1 The UKENVI CGE Model

To identify the general equilibrium impacts, we use a variant of the UKENVI CGE modelling framework. This is an energy-economy-environment version of the basic AMOS CGE framework, calibrated on UK data (Allan *et al.* 2007; Harrigan *et al.* 1991 and Turner, 2009).[13] However, in contrast to previous applications of UKENVI, in this version consumption and investment decisions reflect inter-temporal optimization with perfect foresight (Lecca et al. 2010).

We identify the same twenty one economic activities (commodities/sectors) as considered in the input-output analysis in Section 4. There are three domestic transactor groups:

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[13] AMOS is an acronym for A micro-macro Model Of Scotland. Whilst AMOS was initially calibrated on Scottish data, it is a flexible modelling framework incorporating a wide range of possible model configurations which can be calibrated to data for any small open regional or national economy.

government, households and firms. In this application government expenditure is fixed in real terms. Households optimise their lifetime utility, which is a function of consumption C_t taking the following form:

$$U=\sum_{t=0}^{\infty}\left(\frac{1}{1+\rho}\right)^{t}\frac{C_t^{1-\sigma}-1}{1-\sigma} \tag{15}$$

where C_t is the consumption at time period *t*, σ and ρ are respectively the constant elasticity of marginal utility and the constant rate of time preference. The intra-temporal consumption bundle, C_t, is defined, as in the partial equilibrium simulations, as a CES combination of energy and non-energy composites, as given in equation (5) in Section 2. In our empirical analysis we consider consumption of both domestic and imported energy and non-energy goods, where imports are determined through an Armington link and are therefore relative-price sensitive (Armington, 1969).

The consumption structure is shown in Figure 2. Total consumption is divided in energy and non-energy goods and services. The consumption of energy is then a CES combination of two composites: gas and electricity, and oil and coal. The production structure as imposed in each sector is shown in Figure 3. In each sector the input decision involves a hierarchy of CES relationships between inputs of intermediate goods, labour and capital.

The path of investment is obtained by maximizing the present value of the firm's cash flow given by profit, π_t, less private investment expenditure, I_t, subject to the presence of adjustment cost $g(x_t)$ where $x_t=I_t/K_t$:

$$Max\ \sum_{t=0}^{\infty}\frac{1}{(1+r)^t}\left[\pi_t-I_t\left(1+g(\omega_t)\right)\right]\ \text{subject to}\ \dot{K}_t=I_t-\delta K_t \tag{16}$$

The solution of the dynamic problem gives us the law of motion of the shadow price of capital, λ_t, and the time path of investment related to the tax-adjusted Tobin's *q*.

The UK labour force is assumed to be fixed, with the real wage determined through a wage function that embodies the econometrically derived specification given in Layard *et al.* (1991**):**

$$\ln\left[\frac{w_t}{cpi_t}\right] = c - 0.068\ln[u_t] + 0.40\ln\left[\frac{w_{t-1}}{cpi_{t-1}}\right] \tag{17}$$

where *w*, *cpi* and *u* are the nominal wage after tax, the consumer price index and the unemployment rate respectively, and *c* is a parameter which is calibrated so as to replicate equilibrium in the base year.

In each sector, exports are determined by a standard export demand function.

In our second scenario, the increased energy efficiency in household consumption is directly reflected in the real wage determination given in equation (17). This involves modifying the *cpi* so that the price of energy services is expressed in efficiency units. In the conventional approach, cpi is simply as a function of the price of commodities:

$$cpi = cpi(p_{NE}, p_E) \quad cpi_{p_{NE}}, cpi_{p_E} \geq 0; \tag{18}$$

where p_{NE} is the price of non-energy goods and services and p_E is the price of energy services, both measured in natural units. If τ is used to identify an efficiency unit of energy, with a γ percentage change in in energy efficiency in household consumption, we can incorporate the efficiency change in the wage bargaining process by simply adjusting the *cpi* by measuring the price of energy in efficiency units. This goes as follows:

$$p_\tau = \frac{p_E}{1+\gamma} < p_E \quad \text{for } \gamma > 0 \tag{19}$$

So that

$$cpi_{\tau} = cpi(p_{NE}, p_{\tau}) \qquad (20)$$

where p_{τ} is the price of energy measured in efficiency units. This means that with constant energy prices in natural units, p_E, an improvement in energy efficiency reduces the price of energy in terms of efficiency units, p_{τ}. In this scenario, this reduces the *cpi* and has a direct effect on the nominal wage rate.

5.2. Calibration and key model parameters

The model calibration process assumes the economy to be initially in steady state equilibrium. The key dataset is the UK Social Accounting Matrix, which incorporates the 2004 Input Output table used in Section 4. However, we need also to impose a number of important behavioural parameters. First, as in all the partial equilibrium simulations, we adopt the estimated values for the short- and long-run elasticity of substitution between energy and non-energy goods and services in household consumption given in Section 3. Trade elasticities are set equal to 2 (Gibson, 1990) and production elasticities equal to 0.3 (Harris, 1989). The interest rate (faced by producers, consumers and investors) is set to 0.04, the rate of depreciation to 0.15 and with constant elasticity of marginal utility equal to 1.2 (Evans, 2005).

5.3 Simulation strategy

As in the partial equilibrium simulations, we introduce a costless and permanent step efficiency increase of 5% in energy use in household consumption. We report results for two conceptual time periods, the short run and the long run. We also report period-by-period impacts for some simulations. The short-run corresponds to the first period of the simulation, where the initial capacity constraints are present. That is to say, in this time interval the capital stock is fixed, both in its total and its sectoral composition, at the base period values. However, from period two, capital stock adjusts through investment and depreciation. In the long run, the state variables of the model are subject to transversality conditions, so as to obtain a new steady-state.

As discussed in Section 4, the appropriate value to use for the elasticity of substitution between energy and non-energy commodities in household consumption is not straightforward. When the analysis applies to the long run, we always use the long-run elasticity of substitution. However, in the short run, as argued in Section 3, we perform simulations using both the short-run and long-run substitution elasticities.

6. General Equilibrium rebound results

Table 4 shows the impact of the improved household energy efficiency on key macroeconomic variables using the conventional perfect foresight AMOS model. We label this Scenario 1. We report the results as percentage changes from the base year values. The short-run figures are given for both the short- and long-run estimated values of the elasticity of substitution between energy and non-energy commodities in household consumption. Recall, that we argue there that the long-run elasticity values might be more appropriate, even in short-run simulations, if energy efficiency is embodied in the design of consumer durables. In Scenario 2, the model is adjusted, as shown in in equation (19) and (20) in Section 5.1, so that the cpi incorporates the price of energy in efficiency, rather than natural, units. In Table 6, the results from this simulation are reported.

6.1 Scenario 1: The standard model

The simulation results using the standard AMOS model are given in Table 4. In the short run in Scenario 1, employing the short-run elasticity of substitution generates a 2.64% reduction in household energy consumption. The switch in household expenditure towards non-energy consumption has a small expansionary impact on the economy: total output, consumption and investment increase by 0.04%, 0.22% and 0.14% respectively.[14] There is a corresponding stimulus to labour demand, lowering the unemployment rate by 0.23% and increasing the real wage by 0.03%.

The fall in the household demand for energy is accompanied by a fall in industrial demand of 0.24% because of the energy intensity of the production of energy itself. The total energy use and output fall by 1.07% and 0.87% respectively. The proportionate changes in production for the individual energy sectors is given in Figure 5, with production in coal, oil, gas and electricity falling by 0.98%, 0.38%, 1.27% and 0.97% respectively. In the short run, the reduction in domestic demand in the coal, gas and electricity sectors is partially offset by an increase in exports and import substitution. This is produced by the increase in competitiveness shown in the fall in energy prices as depicted in Figure 6. These reductions are caused by the emergence of overcapacity in those sectors in the short run following the efficiency improvement.

The second column of Table 4 reports the short-run impacts where the long-run elasticity of substitution between energy and non-energy goods and services is imposed. Note that in this case there is a smaller reduction in household consumption of energy of 1.42%. This means

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[14] The consumption value is the change in real consumption so that the increase in efficiency in the household use of energy would be registered as a stimulus to real consumption, even if the nominal household income and prices were held constant.

that there is less expenditure switching, which has two general implications. The first is that the expansionary impacts, whilst still present, are all slightly smaller than where the short-run elasticity is used. This is because non-energy expenditure has a greater impact on the UK economy than the same amount of expenditure on energy. The second is that the total reduction in energy use is also lower, at 0.57%.

In the long run results, shown in the third column in Table 4, household consumption of energy, energy demand by industry, total energy use and total energy output all remain below their base-year values. However, there is a 0.10% increase in GDP and similar increases in total employment and investment. The expansion in the long run is greater than in the short run as the ability to adjust capacity allows a greater response to the net positive demand stimulus. Because the labour force is assumed to be fixed, there is a fall in the unemployment rate generating an increase in the real wage which, in turn, puts upward pressure on all commodity prices and reduces competitiveness. This is shown in Figure 6.

Figure 7 reports the percentage change in sector prices relative to the base year level for the whole period of adjustment, using the long-run elasticity of substitution value in each time period. The demand shock generates short-run shifts in prices which reflect the change in household demand. There are short-run price reductions in coal, gas and electricity but corresponding price increases in all other sectors. Over time, the adjustment of capacity leads to small increases in prices in all sectors. The long-run price behaviour differs from that generally obtained where the energy efficiency improvement applies to the production side of the economy. For improvements in energy efficiency in production, economic activity is stimulated through downward pressure on the prices. This includes the price of energy output itself since the energy supply sector is typically energy intensive.

While the increase in total investment in Scenario 1 means that there is an increase in capital stock in non-energy sectors in response to the efficiency improvement, decreased output in the energy sectors lead to a contraction in their capital stocks. The trigger for this disinvestment is the fall in the shadow price of capital caused by the initial contraction in demand for energy sector outputs. Energy firms' profit expectations therefore fall. This is reflected in Figure 8, where we plot the shadow price of capital and the replacement cost of capital for the energy sectors. In each of these sectors, the shadow price of capital is below the replacement cost of capital over the entire adjustment path, implying that Tobin's q < 1 in these sectors. Ultimately, there is complete adjustment where the capital stock reaches the steady-state equilibrium. After the initial fall, the price of energy rises over time, allowing the shadow price of capital to converge on the replacement cost of capital, so that Tobin's q asymptotically approaches unity.

Again, using equations (1) and (2) and the household and total energy change figures identified in this section we can calculate the household and total energy rebound effects. These are reported in rows 2 and 3 of Table 3 for the composite energy use and Table 5 for specific energy sectors. We begin by giving the results for the energy composite which are shown in Table 3. In the short-run simulations the rebound values for household energy use are 47.3%, using the short-run elasticity of substitution, and 71.6% for the long-run value. The corresponding short-run general equilibrium rebound values for total energy use are 38.5% using the short-run elasticity of substitution and 67.1% with the long-run. For the long run values (which always use the long-run substitution elasticity) the household rebound is 67.6% and the total rebound is 59.3%.

Table 5 shows the general equilibrium rebound effects for individual energy sectors. The variation across sectors in household rebound is relatively low, with the order of the sector (from highest to lowest) as: gas, electricity, oil and coal. These differences are driven, in the model, solely by variations in the prices of the different energy sectors. On the other hand, the variation in the economy-wide rebound values across the individual energy sectors is very large.

To understand these wide variations it is important to begin by noting precisely what is being measured here. First, the improvement in household energy efficiency is occurring across all energy sectors, not just the energy sector whose rebound value is being calculated. Second, this is a measure of the change in total use of that energy type as measured against its initial household use.

The most distinctive element of these results is the very large negative rebound values for coal. For example, the short-run value using the short-run substitution elasticity implies that for the 5% increase in energy efficiency there is a fall in total coal use equal to 1.38% of the initial household consumption of coal. This reflects the heavy employment of coal as an intermediate input in the production in other energy sectors, particularly electricity, coupled with its relatively small use by households. This means that the reduction in the output of other energy sectors has a relatively large negative impact on the use of coal. In all the simulations, the coal sector has a large negative rebound, implying that the fall in its total use is greater in absolute terms than 5% of the initial household consumption of coal. For all the other energy sectors the economy-wide rebound is positive, although clearly the role of gas as an intermediate in the production of electricity reduces the rebound value for that sector.

6.2 Scenario 2: Measuring energy prices in efficiency units for the consumer price index

In Scenario 1, the increase in energy efficiency in the household sector acts in a way that is observationally equivalent to a change in tastes. This is because, as shown in equation (14), in the calculation of the real wage, the consumer price index, *cpi*, combines the price of non-energy and energy commodities measured in natural units. However, it might be more appropriate in defining the *cpi* to measure the composite energy price in efficiency units. This implies that the *cpi* should be calculated as in equations (15) and (16). With this approach, in so far as improvements in energy efficiency reduce the energy price (measured in efficiency units), this will be translated into a fall in the cpi, which will put downward pressure on the nominal wage and serve as a source of improved competitiveness.

Scenario 2 repeats the simulation of a 5% step increase in energy efficiency in household consumption. All aspects of the simulations are exactly the same as those reported for Scenario 1 in Section 6.1, apart from the difference in the calculation of the *cpi*. The percentage changes in key economic variables are reported in Table 6 and the corresponding rebound values in Table 7. The change in the prices for individual commodities over time is given in Figure 9.

In the standard case reported as Scenario 1, both the *cpi* and the nominal wage rise and are maintained above their base year values in the long run. However, in the simulation where the price of energy in is measured in efficiency units, these results are reversed. In the short run, using either the short-run or long-run household consumption substitution elasticity generates a fall in the nominal wage of 0.13% and 0.11% respectively. The fall in the nominal wage in the long run is 0.11%. As shown in Figure 9, this reduction in the labour input costs shows that there is a net decrease in the price of output in all production sectors. Thus with this simulation there is a much larger stimulus to GDP, employment and investment than under Scenario 1. All these aggregate activity variables increase in the long run by around 0.25%.

There will be impacts on the changes in energy prices, household income and GDP that accompany the household energy efficiency improvement. The reduction in energy use is always bigger in Simulation 1 than in the corresponding result in Simulation 2. That is to say, the bigger stimulus to the economy in Simulation 2 reduces the energy saving. However, the impact on energy use and the associate rebound effects are small. Even in the long run, where the relative expansionary impact of the increased energy efficiency is greatest, the total energy rebound for Scenario 2 is 54.28, against the Scenario 1 figure of 48.46.

7. The value added from a general equilibrium analysis

In comparing the general and partial equilibrium analysis, and therefore the value added from a general equilibrium approach, we begin by considering the rebound values for the simulations in Scenario 1, reported in Tables 3. A cursory glance at the results reported in Figure 3 shows that same basic data can generate a wide range of possible rebound values. The rebound value depends upon the narrowness of the focus of the analysis, the value of key parameters, the time scale and whether a partial or general equilibrium approach is adopted.

The first row in Table 3 gives the partial equilibrium values. Recall that this corresponds to the rebound on an individual household's energy consumption if that household alone were making the energy efficiency with money income and energy prices unchanged. The household energy rebound focusses solely on the direct energy use by households. The first point to make is that we do not require general equilibrium effects to get substantial rebound values. Further, the larger the elasticity of substitution between energy and non-energy in household consumption, the greater the rebound will be. Second, the total rebound values are less than the household consumption values, as argued in Section 4.2. This reflects the shift of household expenditure away from the intermediate demand energy intensive energy sectors towards less energy intensive commodities and services. Moreover, the difference between the total and household consumption rebound values falls as the household consumption value increases, as shown in Figure 1.

Moving to a general equilibrium analysis involves incorporating the effect on energy use of the impact of endogenous changes in prices, wages and incomes. In Scenario 1, the effect on household consumption of energy is to increase the rebound effect by around 10 percentage points. This increase in the short-run household rebound between the partial and the corresponding general equilibrium value is the result of the change in income and prices captured under general equilibrium. Household income increases in real term by around 0.06% in the short run (for both short- and long-run elasticities). Given income elasticity equal to one, we should expect a similar increase in energy consumption (although the linearity assumption between income and consumption does not strictly hold here given the perfect foresight of households). Therefore we expect household income changes to increase the general equilibrium rebound values by around 1.2 percentage points. The relative price changes, shown in Figure 5 generate the remaining, larger, rebound effects. The short run significant falls in energy prices leads to the substitution of energy for other commodities in the household budget.

The change between the partial and general equilibrium values for the rebound in total energy use is much larger than the household rebound. Note that these total energy rebound figures are around 20 percentage points higher under general equilibrium than partial equilibrium. Again household income changes contribute around 2 percentage points[15]. Prices play a much

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[15] Change in real income is around 0.10% from base year value. Generally in the long-run we would expect that change in income equate change in consumption. However, given that the shock implies a shift in consumption due to an increase in efficiency the total change in consumption are higher than change in current income and total household wealth.

more important role here. There will be a substitution of energy or non-energy commodities as intermediate inputs plus the rise in the price of non-energy commodities will reduce their output as exports fall and import substitution takes place.

Each long-run general equilibrium rebound figure should be compared to the corresponding short-run general equilibrium and the partial equilibrium values. These comparisons should be made amongst simulations which use the long-run elasticity of substitution in household consumption. For both the household and total energy rebound, the long-run general equilibrium value lies between the corresponding partial equilibrium and short-run general equilibrium figures.

The long-run general equilibrium simulations generate larger positive changes in household income and GDP than the partial equilibrium or short-run general equilibrium values. However, as a result of adjustments in the capital stock, generally requiring disinvestment in energy sectors but expansion in the capacity of non-energy sectors, over time the price variation between sectors in general equilibrium is much reduced and finally driven only by the relative impact of the higher nominal wage across different sectors. This means that the substitution and adverse competitiveness effects that increase the rebound effects under short-run general equilibrium are much reduced in long-run equilibrium.

Table 5 shows the rebound effects identified for individual energy types. In household consumption all energy types are assumed to have the same elasticity of substitution with non-energy household consumption. Therefore in the partial equilibrium results household rebound in all energy sectors will be the same as the energy sector as a whole: 36.90 and 62.20 with short-run and long-run elasticities respectively. However, there are big variations in the partial equilibrium total energy use rebound figures across different energy types. This reflects the different use of the energy sectors as intermediates compared to their use in household consumption.

In the sector-disaggregated general equilibrium the variation in household rebound is driven by variation in output price across he different energy sectors. This is relatively limited. However, again the total energy use rebound values are more strongly dominated by variation in the use of different energy sources as intermediate inputs, compared to their use in final consumption.

In Scenario 2, the improvement in household efficiency in the use of energy is allowed to feed through to increased competitiveness via downward pressure on the nominal wage. The short-run and long-run general equilibrium rebound results are given in Table 7. If these results are compared with the corresponding rebound values reported in Table 3 the following results emerge.

First, the incorporation of this additional general equilibrium effect has almost no effect on the household rebound values in either the short or long-run. Whilst the employment is higher in the simulations under Scenario 2, compared to the corresponding simulations in Scenario 1, the nominal wage is lower so this has an offsetting effect on energy consumption. Also energy production is relatively capital intensive so that there the relative price of energy will generally rise against other household consumption, which will tend to reduce energy consumption. Also in the model a number of transfers are fixed in real terms, so that when the cpi falls the nominal value of these transfers also falls.

Second, for the total energy use rebound values, the Scenario 2 values are always higher than their Scenario 1 counterparts. The greater expansion of GDP under Scenario 2, together with the fact that the efficiency of energy use in production has not been increased, produces this result. However, the differences are quite modest, the largest being for the long-run rebound value which increases by 4.6 percentage points to 63.95% in Scenario 2.

8. Conclusions

The main contribution of this paper is to study the impact of efficiency improvement in the use of energy in household consumption and show the resulting partial and general equilibrium household and total energy rebound values. We examine the partial equilibrium rebound effects using a framework in which prices and nominal incomes are assumed fixed. To calculate the total energy use we adopt the conventional Type I Input-Output model. For the general equilibrium impacts a Computable General Equilibrium (CGE) framework is adopted. We use two forms of the CGE model. One is the standard version. The second allows the increase in household efficiency in the use of energy to improve competitiveness through downward pressure on the nominal wage.

The results summarised in Tables 3 and 7 serve both a practical and conceptual purpose. They indicate the range of rebound values that can be derived from a given basic data set, depending on the precise way that the rebound measure is specified. However, these results also show how the long-run total energy general equilibrium rebound value can be deconstructed to reveal the relative size of the various effects. Let us begin with partial equilibrium. First, note that the value of the elasticity of substitution between energy and non-energy commodities in household consumption is important in determining the rebound value. This appropriate elasticity value depends not only on the time period under consideration but also whether the efficiency improvement is embedded in the design of household durable goods or not. Second, we strongly identify the negative impact on the rebound value when the focus shifts from household consumption to total energy consumption. This phenomenon reflects the relative energy intensity of energy production itself. This means that when direct household consumption of energy falls, indirect consumption of energy falls also, reducing the total rebound.

The substitution elasticity and intermediate input effects identified under partial equilibrium remain largely undiminished in the general equilibrium analysis. However, general equilibrium also incorporates the impact of relative price, income and activity. We observe that the main additional general equilibrium impacts occur in the short run where the fall in energy prices cushions the fall in energy use. This leads to the short-run general equilibrium rebound values being greater than the corresponding partial equilibrium and long-run general equilibrium values (for the same elasticity of substitution value). In the long run, disinvestment in this model severely reduces the relative price changes that occur in the short run, leaving the rebound values closer to their partial equilibrium counterparts. Further, the expansionary effect of the energy efficiency improvement in this case is relatively limited.

References

Allan, G., Hanley, N., McGregor, P., Swales, J.K., Turner, K., (2007). The impact of increased efficiency in the industrial use of energy: a computable general equilibrium analysis for the United Kingdom. *Energy Economics*, Vol. 29, No. 4, pp. 779–798.

Armington, P. (1969). A theory of demand for products distinguished by place of production. *IMF Staff Papers*, 16, 157-178.

Baker, P. and Blundell R., (1991). The Microeconometric Approach to Modelling Energy Demand: Some Results for UK Households. *Oxford Review of Economic Policy*, Vol. 7 No. 2, pp. 54-76.

Baker, P., Blundell, R., and Micklewright, J. (1989). Modelling Household Energy Expenditures Using Micro-data. *Economic Journal*, 99, No. 397, pp. 720-738.

Brookes, L., (1990). The greenhouse effect: the fallacies in the energy efficiency solution. *Energy Policy*, Vol. 18, No. 2, pp. 199–201.

Department of Energy and Climate Change, (2010). Energy Consumption in the United Kingdom.
London. Http://www.decc.gov.uk/assets/decc/statistics/publications/ecuk/file11250. pdf

Dimitrooulos, J., (2007). Energy productivity improvements and the rebound effect: An overview of the state of knowledge. Energy Policy, Vol. 35, N.12, pp. 6354–6363.

Druckman, A., Chitnis, M., Sorrell, S. and Jackson, T. (2011) Missing carbon reductions? Exploring rebound and backfire effects in UK households. Energy Policy, in press, doi.10.1016/j.enpol.2011.03.058.

Dubin, J.A., Miedema, A.K., Chandran, R.V., (1986). Price effects of energy-efficient technologies: a study of residential demand for heating and cooling. *Rand Journal of Economics*, Vol. 17, No. 3, pp. 310-325.

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, No. 1, pp. 69–90.

European Commission (2009) EU action against climate change: leading global action to 2020 and beyond. Available to download at: http://ec.europa.eu/clima/publications/docs/post_2012_en.pdf

European Commission (2011) Energy Efficiency Plan 2011. Available to download at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0109:FIN:EN:PDF.
Evans, D.J., (2005). The Elasticity of Marginal Utility of Consumption: Estimates for 20 OECD Countries. Fiscal Studies, Vol. 26, No. 2, pp. 197-224.

Freire-Gonzalez, J., (2010). Empirical Evidence of Direct Rebound Effects in Catalinia. Energy Policy, Vol. 38, No. 5, pp. 2309-2314.

Freire-Gonzalez, J., (2011).Methods to Empirically Estimate Direct and Indirect Rebound Effect of Energy-Saving Technological Changes in Households. *Ecological Modelling*, Vol. 223, No. 1, pp.32-40.

Frondel M, Peters J., and Vance C., (2008). Identifying the Rebound: Evidence from a German Household Panel. *The Energy Journal*, Vol. 29, No. 4, pp. 145-163.

Gibson, H. (1990). Export competitiveness and UK sales of Scottish manufacturers. Working paper, Scottish Enterprise. Glasgow, Scotland.

Golan A., Judge G, Miller D. (1996). Maximum Entropy Econometrics: Robust Estimation with Limited Data. John Wiley & Sons: New York.

Gørtz, E., (1977). An Identity between Price Elasticities and the Elasticity of Substitution of the Utility Function. The Scandinavian Journal of Economics, Vol. 79, No. 4, pp. 497-499.

Greene, D.L., Kahn, J.R., Gibson, R.C., (1999). Fuel Economy Rebound Effect for U.S. Household Vehicles. *The Energy Journal*, Vol. 20, No. 3, pp. 1-31.

Greening, L.A., Greene, D.L., Difiglio, C., (2000). Energy Efficiency and Consumption - the Rebound Effect - A Survey. *Energy Policy*, Vol. 28, No. 6-7, pp.389-401.

Guerra, A. I. and Sancho, F., (2010). Rethinking Economy-Wide Rebound Measures: An Unbiased Proposal. *Energy Policy*, Vol. 38, No. 11, pp. 6684-6694.

HM Government, (2007), Meeting the Energy Challenge. A White Paper on Energy. Department of Trade and Industry.

Hanley ND, McGregor PG, Swales JK, Turner KR., (2009). Do increases in energy efficiency improve environmental quality and sustainability?, *Ecological Economics*, Vol. 68, No. 3, pp.692-709.

Harrigan, F., McGregor P., Perman R., Swales K. and Yin Y., (1991), AMOS: A Macro-Micro Model of Scotland, *Economic Modelling*, Vol. 8, No. 4, pp. 424-479.

Harris, R., (1989). *The growth and structure of the UK regional economy, 1963-1985*. Aldershot: Avebury.

Jevons, W. S. (1865) *The Coal Question-Can Britain Survive?*, First published in 1865, reprinted by Macmillan in 1906. (Relevant extracts appear in *Environment and Change*, February 1974.)

Khazzoom, J.D., (1980). Economic implications of mandated efficiency in standards for household appliances. *Energy Journal*, Vol. 1, No.4, pp. 21-40.

Khazzoom, J.D., (1987). Energy savings from the adoption of more efficient appliances. *Energy Journal*, Vol. 8, No. 4, pp. 85-89.

Klein, Y.L., (1985). Residential energy conservation choices of poor households during a period of rising energy prices. *Resources and Energy*, Vol. 9, No. 4, pp. 363-378.

Klein, Y.L., (1987). An econometric model of the joint production and consumption of residential space heat. *Southern Economic Journal*, Vol. 55, No. 2, pp. 351-359.

Lecca P., P. McGregor and J.K. Swales (2011). Myopic and Forward Looking Regional CGE Models. How do they differ?. Strathclyde Discussion Paper.

Lecca, P., J.K. Swales and K. Turner (2011a) Rebound effects from increased efficiency in the use of energy by UK households. Strathclyde Discussion Papers in Economics, 11-23.

Lecca P., J.K. Swales and K. Turner (2011b). An investigation of issues relating to where energy should enter the production function. *Economic Modelling*, Vol. 28, No. 6, pp. 2832-2841.

McGregor, P.G., J.K. Swales and Yin, Y.P. 1996. A Long-Run Interpretation of Regional Input-Output Analysis. Journal of Regional Science, 36; 479-501.

Miller R.E. and Blair P.D, (2009). Input-Output Analysis. Foundation and Extension. Cambridge University Press.

Nadel, S.M., (1993). The take-back effect: fact or fiction? Proceedings of the 1993 Energy Program Evaluation Conference, Chicago, Illinois, pp. 556-566.

Saunders, H.D., (1992). The Khazzoom–Brookes postulate and neoclassical growth. The *Energy Journal,* Vol. 13, No. 4, pp. 131–145.

Shariful Islam A.R. and Morison J.B., (1992). Sectoral Changes in Energy Use in Australia: an Input-Output Analysis. Economic Analysis and Policy, Vol. 22, No. 2, pp. 161-175.

Sorrell, S. and Dimitropoulos, J., (2007). The rebound effect: microeconomic definitions, limitations and extensions. *Ecological Economics*, Vol. 65, No. 3, pp.636–649.

Sorrell, S. (2009). Jevons' Paradox revisited: the evidence for backfire from improved energy efficiency. *Energy Policy*, Vol., 37, No. 4, pp. 1456-1469.

Sorrell, S., Dimitropoulos, J., Sommerville, M., (2009). Empirical estimates of the direct rebound effect: A review. *Energy policy*, Vol. 37, No.13, pp. 1356-1371.

Schwartz, P.M., Taylor, T.N., (1995). Cold hands, warm hearth? Climate, net takeback, and household comfort. *Energy Journal*, Vol. 16, No.1, pp. 41-54.

Turner, K., (2009). Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy, Energy Economics, Vol. 31, No.5, pp. 648-666.

West, S. E., (2004). Distributional effects of alternative vehicle pollution control policies. Journal of Public Economics, Vol. 88. No. 3-4, pp. 735-757.

Table 1

The aggregation scheme for the AMOS 21-sector model

Aggregated IO Sector	**Original Sector Number Included from 123 UK IO**
Agriculture, forestry and logging	1+2
Sea fishing and sea firming	3
Mining and extraction	5+6+7
Food, drink and tobacco	8-20
Textiles and clothing	21-30
Chemicals etc	36-53
Metal and non-metal goods	54-61
Transport and other machinery, electrical and inst eng	62-80
Other manufacturing	31-34+81-84
Water	87
Construction	88
Distribution	89-92
Transport	93-97
Communications, finance and business	98-107+109-114
R&D	108
Education	116
Public and other services	115+117-123
Coal (Extraction)	4
Oil (Refining and distribution of Oil and Nuclear)	35
Gas	86
Electricity	85

Table 2

The direct and Type I energy coefficients (UK, 2004)

	Direct input-output coefficients				Type I embodied energy multipliers			
	Coal	Oil	Gas	Electricity	Coal	Oil	Gas	Electricity
Agriculture, forestry and logging	0.00	0.02	0.00	0.01	0.00	0.02	0.01	0.02
Sea fishing and sea firming	0.00	0.09	0.02	0.04	0.00	0.11	0.03	0.07
Mining and extraction	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.02
Food, drink and tobacco	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.03
Textiles and clothing	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.03
Chemicals etc	0.00	0.00	0.01	0.02	0.00	0.01	0.02	0.05
Metal and non-metal goods	0.00	0.01	0.01	0.02	0.00	0.01	0.02	0.06
Transport and other machinery, electrical and inst eng	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.03
Other manufacturing	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.03
Water	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.03
Construction	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01
Distribution	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.02
Transport	0.00	0.04	0.00	0.00	0.00	0.05	0.00	0.02
Communications, finance and business	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01
R&D	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.02
Education	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01
Public and other services	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02
Coal	0.05	0.02	0.01	0.04	1.06	0.03	0.02	0.07
Oil	0.00	0.02	0.00	0.01	0.00	1.02	0.01	0.03
Gas	0.00	0.01	0.09	0.15	0.01	0.01	1.12	0.24
Electricity	0.05	0.01	0.07	0.28	0.07	0.02	0.11	1.42

Table 3.

Partial and general equilibrium energy rebound values for the standard AMOS model

(Scenario 1)

	ε_{SR}		ε_{LR}	
	Household	Total	Household	Total
Partial Equilibrium.	36.90	15.96	62.20	49.66
Short-Run General Equilibrium	47.27	38.05	71.59	67.10
Long-Run General Equilibrium	-	-	67.61	59.33

Table 4.

The short-run and long-run % change in key economic variables resulting from a 5% increase in household energy efficiency. Standard AMOS model (Scenario 1)

Elasticity of substitution	ε_{SR}	ε_{LR}	ε_{LR}
Time period	Short-run		Long-run
GDP	0.04	0.03	0.10
Consumer Price Index	0.06	0.06	0.03
Unemployment Rate	-0.23	-0.18	-0.40
Total Employment	0.06	0.05	0.10
Nominal Gross Wage	0.09	0.08	0.07
Real Gross Wage	0.03	0.02	0.04
Households Consumption	0.22	0.20	0.25
Investment	0.14	0.16	0.10
Export	-0.08	-0.08	-0.04
Non-Energy Output	0.07	0.05	0.12
Energy output	-0.87	-0.47	-0.61
Energy Use	-1.07	-0.57	-0.70
Energy Demand by Industries	-0.24	-0.12	-0.22
Household Consumption of Energy	-2.64	-1.42	-1.62

Table 5.

Partial and general equilibrium energy rebound values for the standard AMOS model (Scenario 1), disaggregated by energy sectors

	ε_{SR}	ε_{LR}	ε_{LR}
	Short-run		Long-run
General Equilibrium			
Household rebound	47.27	71.59	67.61
Coal	41.97	68.61	67.46
Oil	43.01	69.22	67.49
Gas	50.23	73.21	67.67
Electricity	48.47	72.26	67.65
Economy-wide rebound	38.05	67.10	59.33
Coal	-112.67	-13.41	-21.62
Oil	43.77	70.48	70.62
Gas	41.95	68.94	60.15
Electricity	35.16	65.48	53.25
Partial Equilibrium			
Household Rebound	36.90	62.20	
Economy-wide rebound	15.96	49.66	-
Coal	-53.49	8.05	-
Oil	36.01	61.67	-
Gas	18.30	51.06	-
Electricity	3.81	42.38	-

Table 6

The short-run and long-run % change in key economic variables resulting from a 5% increase in household energy efficiency. Adjusted AMOS model (Simulation 2)

Elasticity of substitution	ε_{SR}	ε_{LR}	ε_{LR}
Time period	Short-run		Long-run
GDP	0.10	0.09	0.24
Consumer Price Index	-0.17	-0.16	-0.22
Unemployment Rate	-0.65	-0.59	-0.99
Total Employment	0.16	0.15	0.25
Nominal Gross Wage	-0.13	-0.12	-0.11
Real Gross Wage	0.04	0.04	0.11
Households Consumption	0.22	0.20	0.29
Investment	0.37	0.39	0.24
Export	-0.02	-0.02	0.06
Non-Energy Output	0.13	0.11	0.25
Energy output	-0.83	-0.43	-0.52
Energy Use	-1.04	-0.54	-0.62
Energy Demand by Industries	-0.19	-0.07	-0.11
Household Consumption of Energy	-2.64	-1.43	-1.59

Table 7

General equilibrium energy rebound values for the adjusted AMOS model (Scenario 2)

	ε_{SR}		ε_{LR}	
	Household	Total	Household	Total
Short-run	47.17	39.80	71.38	68.68
Long-Run			68.20	63.93

FIGURES

Figure 1

The relationship between the partial equilibrium household consumption rebound and total rebound

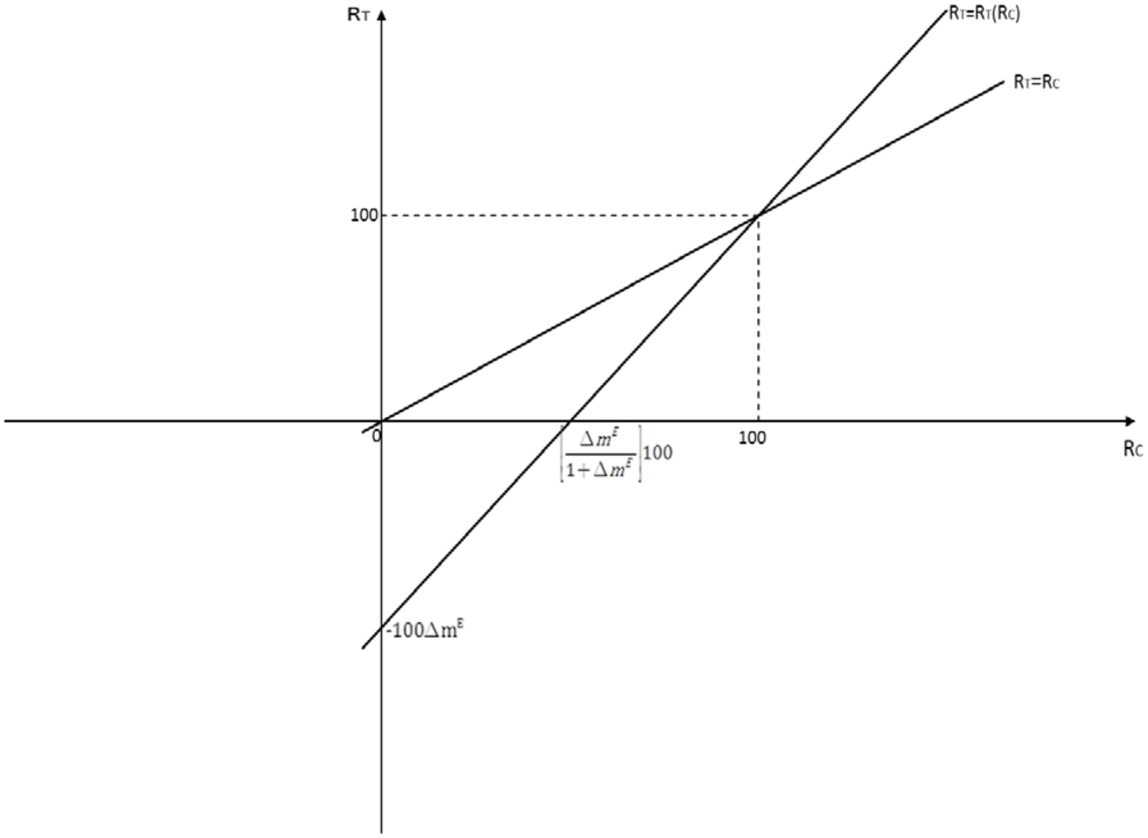


Figure 2

Partial equilibrium (Input-Output) total rebound effects from an increase in household energy efficiency, disaggregated by energy type

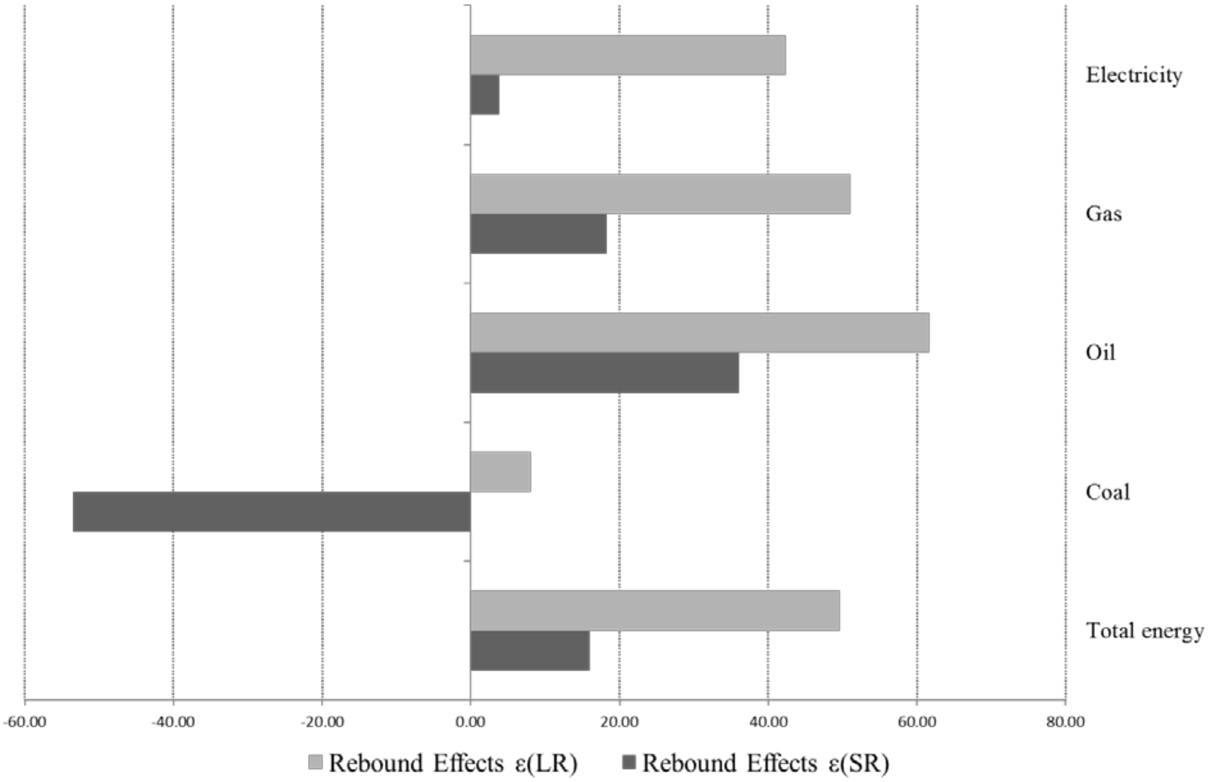


Figure 3

The AMOS model consumption structure

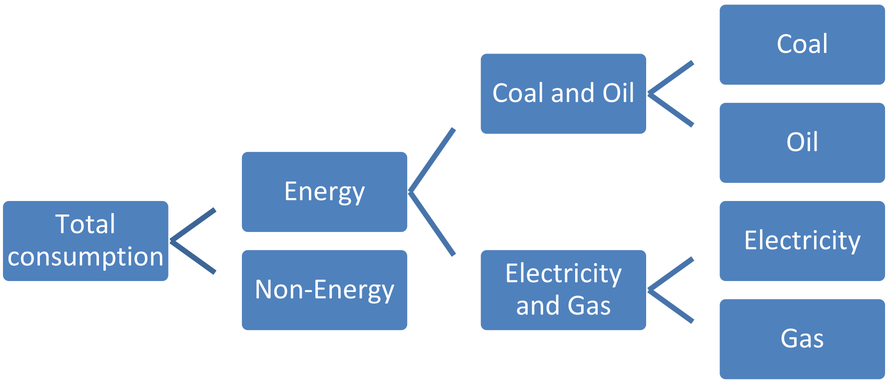


Figure 4

The AMOS model production structure for individual sectors

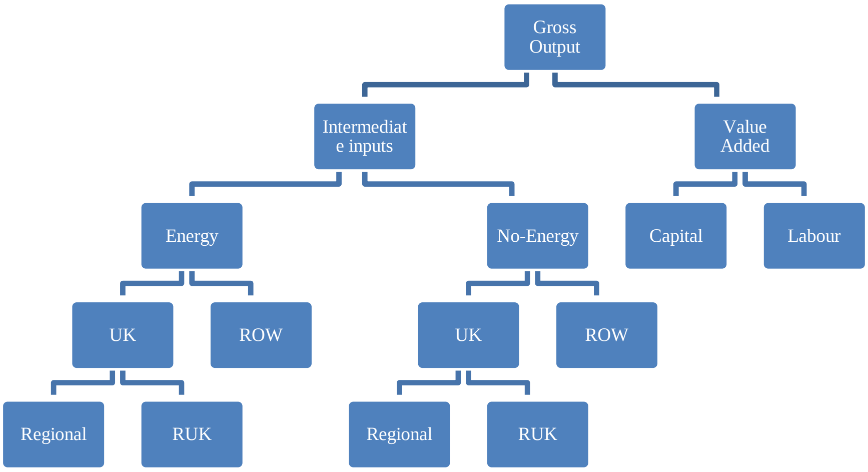


Figure 5

Percentage change in output, investment and export with the standard (Scenario 1) CGE model

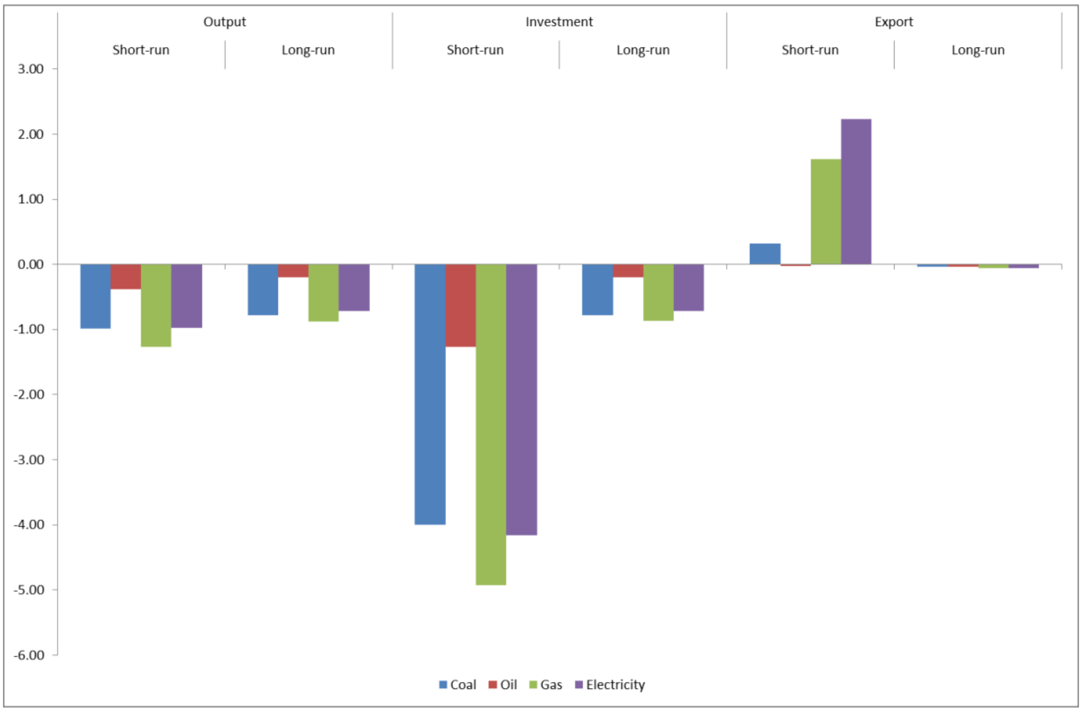


Figure 6

Percentage change in commodity prices with the standard (Scenario 1) CGE model.

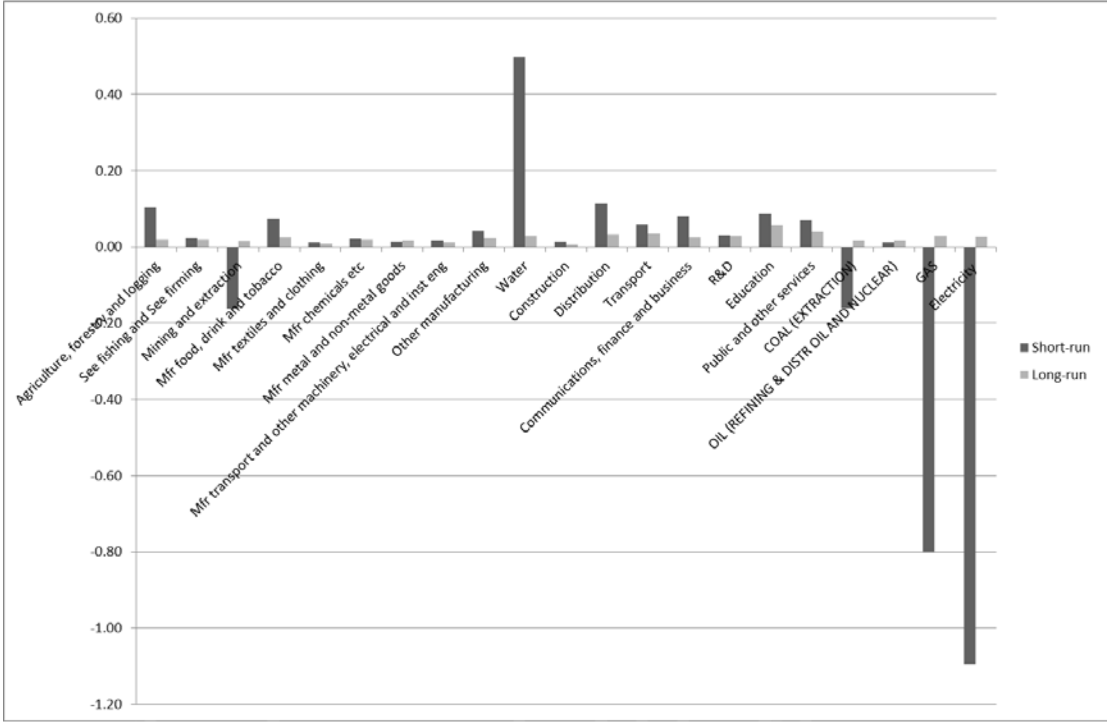


Figure 7
Percentage change in commodity prices with the standard (Scenario 1) AMOS model and long-run substitution elasticities

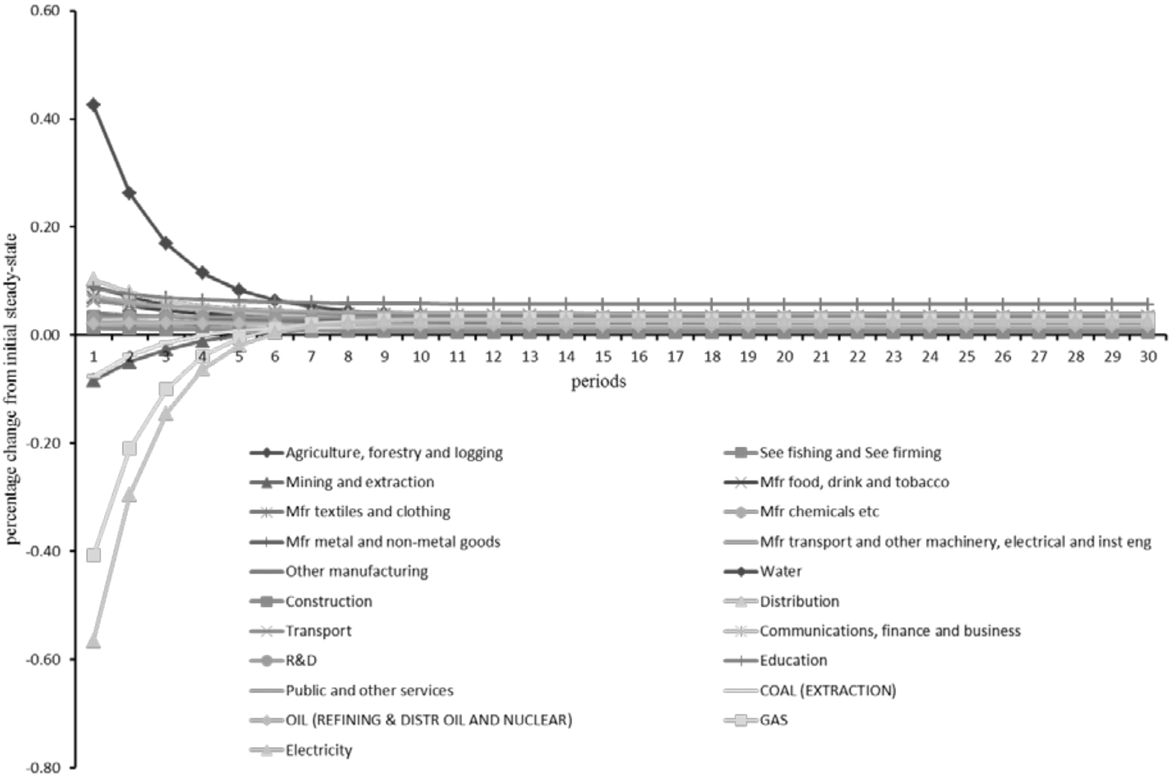


Figure 8
Percentage change in the replacement cost of capital and the shadow price of capital in the energy sector with the standard AMOS model and long-run elasticities of substitution

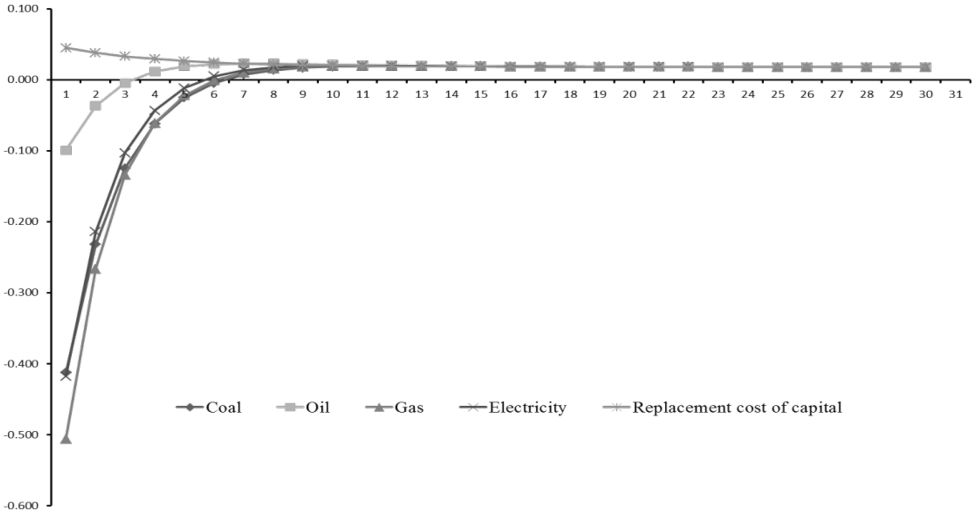
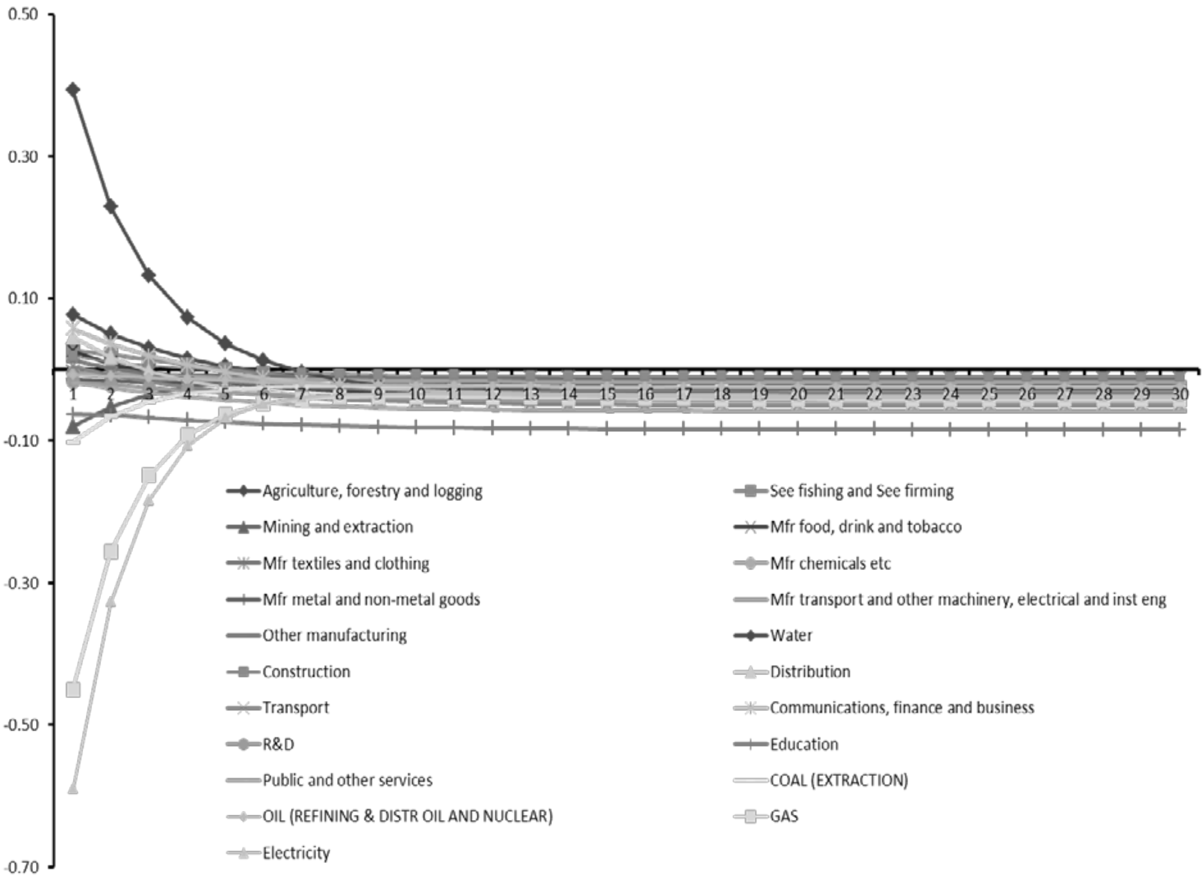


Figure 9.
Percentage change in commodity prices with the adjusted AMOS model and long-run substitution elasticities


0.50
0.30
0.10
-0.10
-0.30
-0.50
-0.70
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Agriculture, forestry and logging
See fishing and See firming
Mining and extraction
Mfr food, drink and tobacco
Mfr textiles and clothing
Mfr chemicals etc
Mfr metal and non-metal goods
Mfr transport and other machinery, electrical and inst eng
Other manufacturing
Water
Construction
Distribution
Transport
Communications, finance and business
R&D
Education
Public and other services
COAL (EXTRACTION)
OIL (REFINING & DISTR OIL AND NUCLEAR)
GAS
Electricity

Appendix

A. Elasticity of substitution between energy and non-energy in the household sector

The value of the elasticity of substitution at the top of the consumption structure (as in Figure 2) is estimated below. From Eq. (4) deriving the first order conditions, taking logs and rearranging, gives:

$$\ln\left[\frac{CNE_t}{CE_t}\right] = \beta_0 + \beta_1 \ln\left[\frac{P_{(E),t}}{P_{(NE),t}}\right] + \mu_t, \qquad \text{(A.1)}$$

where μ is the (*iid*) error term. In this model, the coefficient of interest is β_1 which correspond to the elasticity of substitution between energy and material in the household sector. In order to obtain an estimation for the long-run elasticity of substitution I estimate an autoregressive model of order one (AR(1)):

$$\ln\left[\frac{CNE_t}{CE_t}\right] = \beta_0 + \beta_1 \ln\left[\frac{P_{(E),t}}{P_{(NE),t}}\right] + \beta_2 \ln\left[\frac{CNE_{t-1}}{CE_{t-1}}\right] + \mu_t, \qquad \text{(A.2)}$$

The short and long-run elasticities of substitution are given by β_1 and $\beta_1/(1-\beta_2)$ respectively.

Data on CE_t, $CNE_{,t}$ $P_{(E),t}$ and $P_{(NE),t}$ are required and are shown in Figure A.1 in Appendix C. I use annual data from 1989 to 2008. The energy index price is obtained from the Economic and Social Data Services (ESDS) database[16] while all the other are from the UK

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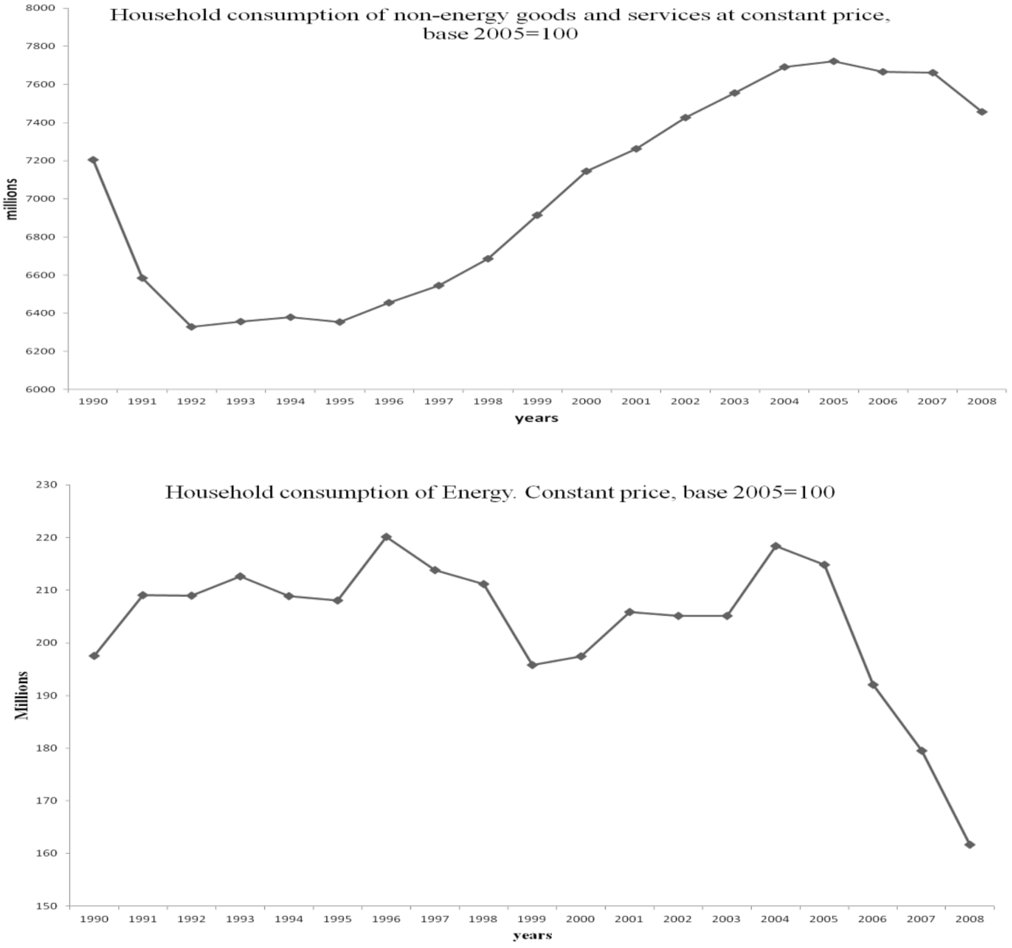
[16] Economic and Social Data Services (ESDS). https://www.esds.ac.uk/.

Office for National Statistical (ONS)[17]. The overall consumer price index is used as a proxy for the non-energy price index.

To estimate the model above we follow a conventional generalized maximum entropy (GME) estimation method (Golan *et al.*, 1996) which is a widely used technique to parameter estimation for CGE models (Jing *et al.*, 2003). We also perform OLS estimations for comparative purposes. A time trend is also introduced in the regression.

Figure A.1. Time series of the household consumption in non-energy goods and services, energy services and price of non-energy (PNE) and price of energy (PE)



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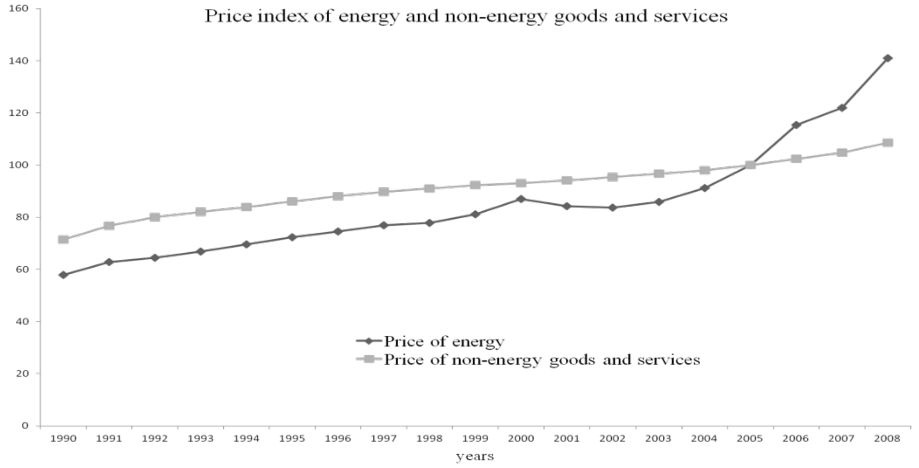
[17] http://www.statistics.gov.uk.



Results of the parameter estimations and the associated confidence intervals are reported in Table 2. The GME confidence intervals are obtained through bootstrap method. Re-sampling has involved 5000 simulations. More details about GME estimation are given in Appendix C.

Table A.1. OLS and GME estimations

				95% confidence interval			
Estimation	**OLS**	**GME**		**OLS**		**GME**	
	Est.	***Est.***		***low***	***high***	***low***	***high***
β_0	**0.850**	**0.848**		**0.41**	**1.29**	**0.31**	**1.14**
β_1	**0.346**	**0.345**		**0.02**	**0.67**	**0.12**	**0.64**
β_2	**0.433**	**0.435**		**0.15**	**0.72**	**0.12**	**0.75**
trend	**0.003**	**0.003**		**0.00**	**0.01**	**0.00**	**0.03**

For the OLS estimation the R^2=; *DW*:; Reset test F(2,33): []; Normality test: $\chi^2(2)$: []

According to the results summurized in Table 2 the GME and OLS estimations yield to identical results. The short and long-run estimates for *ε* are equal to 0.35 and 0.61 respectively. The 95% confidence interval for the elasticity of substitution derived from the GME and OLS estimations are 0.12 - 0.64, and 0.02 - 0.67, respectively. For both models the width of the confidence interval is small and the lower boundaries identify a Leontief relationship for the OLS estimation.