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BY

PATRIZIO LECCA, KIM SWALES AND KAREN TURNER

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DEPARTMENT OF ECONOMICS
UNIVERSITY OF STRATHCLYDE
GLASGOW

Rebound Effects from Increased Efficiency in the Use of Energy by UK Households*

Patrizio Lecca[1,a], Kim Swales[1] and Karen Turner[2]

1. Fraser of Allander Institute and Department of Economics, University of Strathclyde

2. Division of Economics, Stirling Management School, University of Stirling

a. Corresponding author: E-mail:patrizio.lecca@strath.ac.uk;

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Abstract

In this paper, we use CGE modelling techniques to identify the impact on energy use of an improvement in energy efficiency in the household sector. The main findings are that 1) when the price of energy is measured in natural units, the increase in efficiency yields only to a modification of tastes, changing as a result, the composition of household consumption; 2) when households internalize efficiency, the improvement in energy efficiency reduces the price of energy in efficiency units, providing a source of improved competitiveness as the nominal wage and the price level both fall; 3) the short-run rebound can be greater than the long run rebound if the household demand elasticity is the same for both time frames, however, the short run rebound is always lower than in the long-run if the demand for energy is relatively more elastic in the long-run; 4) the introduction of habit formation changes the composition of household consumption, modifying the magnitude of the household rebound only in the short-run. In this period, household and economy wide rebound are lowest for external habit formation and highest when consumers' preferences are defined using a conventional utility function.

Keywords: Energy efficiency; Rebound effects; Households energy consumption; CGE models.

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

1. Introduction

The UK Government's 2007 Energy White Paper considers improved energy efficiency in the household sector a central means of achieving its energy targets of reducing the UK's carbon emissions by 60% by around 2050. According to the Department of Trade and Industry (2010), the domestic final consumption of energy has increased by 19 per cent since 1990 (and by 32 per cent since 1970). The 2004 UK Input-Output Table shows that the households directly account for about 30 per cent of all energy used in the UK. So, it is becoming extremely important to assess the extent to which policies aimed at increasing efficiency in household energy consumption produce the expected energy savings.

An energy efficiency improvement has the benefits of reducing the price of energy services. However, the extent to which such efficiency increase will be effective in reducing the consumption of energy (and thus the associated negative externalities, e.g., CO_2 emissions), is less clear.

In the energy economics literature, it is now accepted that the response to the introduction of new technologies aimed to save energy consumption is likely to be partially (or totally) offset by a reduction in the effective price of energy services[1]. This is what is known as the rebound effect, initially identified by Jevons (1865) and subsequently by Khazzoom (1980). Saunders (1992), in a neoclassical growth framework, emphasizes the possibility of an extreme situation, "backfire", where improvements in energy efficiency do not end up in any energy saving but actually increase the demand for energy[2]. After the work of Khazzoom (1980, 1987) a numbers of studies focus on the rebound effects, at the level of households (Dubin *et al*, 1986; Klein, 1985 and 1987; Nadel, 1993; Schwartz and Taylor, 1995; Greene *et al*, 1999; Waste, 2004; Frondel *et al*, 2008)[3].

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[1] For an extensive survey one can see Brooks (2000), Greening *et al* (2000) and Dimitropoulos (2007).

[2] This is also known as the Khazzoom-Brookes Postulate.

[3] An extensive summary of the extent of rebound on household consumption for several types of energy services can be found in Greening *et al*, (2000).

The common characteristic of the literature listed above is that it is limited to the analysis of rebound at the micro level where only income and substitution effects can be captured (direct rebound). Furthermore, the magnitude of the rebound effect at the household level varies widely because the focus on the activity measured is substantially different in every study. That is, the focus is to consider the efficiency effect on one type of energy services such as personal transportation, residential space heating or cooling. The main result of all of these studies is that an increase in efficiency, will end up in an overall reduction in energy consumption (Greening *et al*, 2000). That is rebound is the more common finding than backfire in the case of household energy efficiency.

There has been increasing interest in examining the nature and magnitude of rebound effects[4] in numerical general equilibrium models. However, to our knowledge, the work presented in Dufournaud *et al*, (1994) constitutes the only study that uses a CGE modelling framework to focus on rebounds effect from increased energy efficiency in the household sector. This study analyses the impact of increasing efficiency in wood stoves in the household sector of Sudan.

A number of authors have examined the impacts of increased energy efficiency within the production side of the economy using CGE models (Semboja, 1994; Grepperud and Rasmussen, 2004; Glomsrød and Taojuan, 2005; Hanley *et al*, 2006 and 2009; Allan *et al*, 2007; Turner, 2009). For instance, the works of Allan *et al*, (2007) and Turner (2009) for the UK, and Anson and Turner (2009) and Hanley *et al*, (2006; 2009) for Scotland evaluate the impact of an increase in energy efficiency in the industrial use of energy. The characteristic of this shock is such that the increase in efficiency introduces a positive supply-side disturbance, whose primary effect is to raise production efficiency, particularly in energy intensive sectors. The efficiency gains stimulate economic activity

[4] A comprehensive review of computable general equilibrium models used to study energy rebound effect can be found in Dimitropoulos (2007).

through downward pressure on the prices, including the price of energy output since the energy supply sector itself is a typically energy intensive.

However a completely different outcome would be observed if the energy efficiency improvement took place in the household sector[5]. The expected results of an increase in energy efficiency in the UK households sector would be a clear example of a simple demand-side shock where households take all prices as given and the supply side effects are thus neglected.

In this paper, we study the economy-wide impacts of increased energy efficiency in the household sector, with particular attention to the conditions under which rebound (or backfire) effects may occur. We apply an intertemporal computable general equilibrium (CGE) modelling framework for the United Kingdom (UK).

In the model, forward looking expectations are incorporated for each of five household income groups (quintiles). Household consumption of energy and other goods and services respectively are modelled as imperfect substitutes, so that the magnitude of the rebound effect is governed by the elasticity of substitution between energy and non-energy goods. The expected energy saving in consumption should be higher the smaller the elasticity of substitution. This is because a lower elasticity reflects less sensitivity to relative price changes and reduces the substitution in favour of energy when its effective price falls. In this case, the efficiency effect would be expected to dominate over the substitution and income effects, so that there is a net decrease in energy use. However, where this elasticity is greater than one, the fall in the effective price of energy will generate a net increase in the household consumption of energy and backfire occurs. Thus, given

[5] In the model outlined below we consider the household sector as a simple component of the final demand for goods and services. That is to say, that we are abstracting from the case in which households are involved in the production of final goods and services through transformation of purchased intermediate commodities. Moreover, we do not consider the case in which households generate energy from their activity by for instance gathering firewood, as in the study of Dufournaud et al, (1994). This may be appropriate for an underdeveloped country, but in the context of the UK economy, it seems reasonable to consider households as a consumer institution which acquires goods and services in the market economy.

that the elasticity of substitution between energy and non energy in the household sector is a key parameter of our model, here we estimate it using a cross entropy method (Golan *et al*., 1996). This estimated elasticity is used in the model simulations to identify the impact of energy efficiency improvement in consumption.

In the initial set up, the consumer price index (*cpi*) is defined as a function of the price of energy plus non-energy commodities, measured in natural units. In this context, the impact of energy efficiency in household consumption is simply to shift demand between consumption goods and services. However, it is more appropriate to readjust the *cpi* by defining the price of energy in efficiency units. This means that changes in efficiency will affect the real wage. Improved energy efficiency reduces the effective price energy, providing a source of improved competitiveness as the nominal wage falls for any given real wage.

In our analysis we also investigate how alternative assumptions about consumers' time preferences affect the magnitude of both the household and economy-wide rebound. We contrast the conventional time-separable lifetime utility specifications with the case where preferences over consumption exhibit habit formation. In doing so, we use a simple specification of habit persistence (as e.g. Boldrin *et al*, 2001) distinguishing between internal and external habit formation (Abel, 1990).

The paper is structured as follows. In the next section we outline the main equations of our modelling framework. Then in Section 3, we outline the method used to estimate the elasticity of substitution between energy and non energy goods and services in the household sectors. In Sections 4, we draw the simulation strategy and Sections 5, 6 and 7 are dedicated to explaining different elements of the results. The paper ends with some sensitivity analysis in Section 8, followed by conclusions in Section 9.

2. Model description

In this paper we develop an intertemporal variant of the UKENVI CGE modelling framework, the energy-economy-environment version of the basic AMOS CGE framework initially developed by Harrigan *et al* (1991)[6]. In contrast to previous applications of UKENVI (Allan *et al*, 2007 and Turner, 2009) here consumption and investment decisions reflect intertemporal optimization with perfect foresight. Three domestic transactor groups are incorporated: households, corporations and government; we identify six economic activities or sectors: *Primary sector*, *Manufacturing*, *Construction*, *Services*, *Other Services* and *Energy*[7].

Consumer Preferences

The economy is inhabited by five lifetime earning groups of households. Each *H*-type household optimises its lifetime utility function of consumption, which takes the form:

$$U^H = \frac{1}{1-\sigma}\int_0^\infty \left[C_t^H - bC_{t-1}^H\right]^{1-\sigma} e^{\rho t}\, dt \qquad (1)$$

Where σ and ρ are respectively the constant elasticity of marginal utility and the constant rate of time preference. For $b > 0$, household preferences are characterized by some degree of habit persistence whilst if $b = 0$, we return to the conventional utility function. The utility function we adopt corresponds to the case where household's habit is related to its own past consumption, C_{t-1}.

[6] AMOS is an acronym for A micro-macro Model Of Scotland, deriving its name from the fact the framework was initially calibrated on Scottish data. AMOS is a flexible modelling framework, incorporating a wide range of possible model configurations, which can be calibrated for any small open regional or national economy for which an appropriate social accounting matrix (SAM) database exists.

[7] See Appendix I Table A.1 for details about aggregation.

This is known in the literature as internal habit. The other common specification of habit preferences links the household's habit to the aggregate economy-wide past consumption, $\overline{C}_{t-1}$ (external habit)[8]. With internal habit, a household's consumption depends on its own past consumption, so that the agent takes into account the effect of his current consumption on his future utility. Thus positive change in consumption at time t lowers the marginal utility of consumption in the same period while increasing it at $t+1$. For the case of external habit or "catching up with the Joneses" (Abel, 1990) consumption of each household is affected by the average level of aggregate consumption ignoring the effects of their own current consumption on future consumption decisions.

The introduction of habit changes the composition of household consumption only in the short-run and in the transitional path towards the long-run equilibrium. In the new steady state the model achieves the same equilibrium, with or without habit. Indeed, the presence of habit introduces a complementary relationship between consumption in two temporally contiguous time period, modifying as a results the speed of convergence between the time-separable utility model and the model with features of non-time separable preferences. We would expect greater consumption smoothing effects for non-time separable utility than for the conventional utility function, given that household with habit persistence would like to maintain the previous standard of living. With habit formation, households have an aversion to changing their consumption in response to a shock, meaning that consumption adjusts more gradually because of the increased desire to smooth the consumption path. The main difference between internal and external habit is that in the latter, habit is seen as an externality. An agent with external habit disregards the impact that his own current consumption produces on his future utility. For the case of internal habit the agent completely

[8] Habit formation is introduced in the model as a simple specification of household's stock of habit bC_{t-1}. Here b is the degree of intensity of habit persistence. See Christiano and Fisher (1998), Abel (1990), Campbell and Cochrane (1999), Boldrin et al. (2001) and Smet and Wouters (2003) for a general discussion on different and more advanced specifications of habit formation.

internalizes the effect of his present consumption decision on the future evolution of his level of expenditure.

The *H*-type household budget constraint is defined as follows:

$$W_t^H(1+r) = W_{t+1}^H + Y_t^H \quad (2)$$

Y is the net income available for consumption, *r* is the exogenous interest rate while *W* is the total wealth, which is defined in the model as the sum of the financial (*FW*) and non-financial wealth (*NFW*).[9]

The consumption bundle C_t^H is defined intra-temporal as a CES combination over non-energy $C_{(NE),t}^H$ and energy goods $C_{(E),t}^H$:

$$C_t^H = \left[a^H \left(A_{(E),t}^H \cdot C_{(E),t}^H \right)^{\frac{\varepsilon-1}{\varepsilon}} + (1-a^H) \left(A_{(NE),t}^H \cdot C_{(NE),t}^H \right)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}} \quad (3)$$

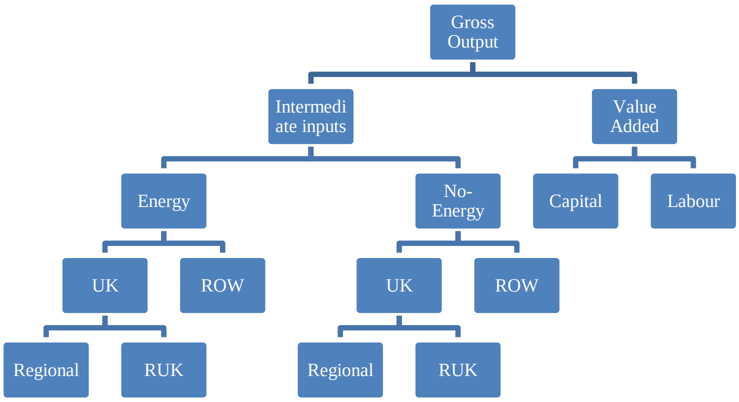
Where ε is the of intra-temporal substitution elasticity, $a^H \in (0,1)$ is the share parameter while A_E^H and A_{NE}^H respectively measure of technical progress for energy and non energy.

Then domestic and imported consumption of energy and non-energy goods are obtained via an Armington link (Armington, 1969) and are therefore relative-price sensitive.

[9] See Lecca *et al*, (2010) for further details.

Figure 1

Production Structure for each sector *i*



Production. The model's production structure is illustrated in Figure 1, involving a hierarchy of CES relationships (with Leontief and Cobb-Douglas as a special case) between different inputs. Intermediate inputs (*VV*), labour (*L*) and capital (*K*) constitute the production inputs of the model. *L* and *K* are combined in a CES production function in order to produce value added, *Y* and VV is defined over Energy and Material[10] (or non-energy input) which can be produced locally or imported. These are considered as imperfect substitutes under the so called Armington assumption through a CES function.

Investment. The path of private investment is obtained by maximizing the present value of the firm's cash flow given by profit, π_t, less private investment expenditure, *I* subject to the presence of adjustment cost $g(x_t)$ where $x_t = I_t / K_t$ (Devarajan and Go,1998, Go, 1994 and Hayashi, 1982):

$$Max \int_0^t \left[\pi_t - I_t\left(1 + g(x_t)\right)\right] e^{-\int_0^t r_v dv} dt \tag{4}$$

subject to $\dot{K}_t = I_t - \delta K_t$

[10] The appropriate specification of the hierarchical structure of the KLEM (Capital, Labour, Energy and Material) production function is still under debate. A systematic sensitivity analysis of where energy should enter the production structure is in Lecca *et al*, (2011).

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 and an adjustment cost parameter z:

$$\frac{I_t}{K_t} = \frac{1}{z}\left[\frac{\lambda_t}{Pk_t} - (1 - v - \tau k)\right];$$
$$\dot{\lambda} = \lambda_t(r + \delta) - rk_t - Pk_t\left[\frac{I_t}{K_t}\right]^2 g'(I_t/K_t); \qquad (5)$$

where *Pk* is the replacement cost of capital, *rk* is the rate of return to capital and *v* is a calibrated parameter.

Labour forces in the present model are fixed[11] and wage setting is determined via a regional bargained real wage function that embodies the econometrically derived specification given in Layard *et al* (1991**):**

$$\ln\left[\frac{w_t}{cpi_t}\right] = c - 0.068\ln[u_t] + 0.40\ln\left[\frac{w_{t-1}}{cpi_{t-1}}\right] \qquad (6)$$

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.

To allow that change in efficiency produces improvement in the quality of energy services to be reflected in the real wage adjustment equation seen above, we modifying the *cpi* by expressing the price of energy in efficiency unit. To simplify the analysis we can generally see the *cpi* as a function of the commodities price:

[11] In other previous work on this topic, for the Scottish economy (Hanley *et al*, 2006 and 2009) labour force adjusts according to the econometrically parameterised net migration function reported in Layard *et al* (1991).

$$cpi = cpi(p_{NE}, p_E) \quad cpi_{p_{NE}}, cpi_{p_E} \geq 0; \tag{7}$$

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. In those simulations where we accommodate quality change in the wage bargaining process, we adjust *cpi* measuring the price of energy in efficiency units, as follows:

$$p_\lambda = \frac{p_E}{1+\lambda} < p_E \text{ for } \lambda > 0 \tag{8}$$

$$cpi_\lambda = cpi(p_{NE}, p_E, \lambda) \tag{9}$$

where p_ε is the price of energy measured in efficiency units. In this new specification positive efficiency shock put downward pressure on the *cpi* affecting the real wage equation, so that claims for higher real wages will be eased by the internalization of the energy efficiency in the local bargaining process.

3. Calibration and key parameters estimation

3.1. Model parameters

The model calibration process assumes the economy to be initially in steady state equilibrium. The dataset is represented by a UK SAM which incorporates the 2004 Input Output table[12] and the classification of households in five income quintiles is in De Fence and Turner (2010).

[12] The core elements of the SAM database is the UK symmetric Input Output Table elaborated by the Frase of Allander Institute.
http://www.strath.ac.uk/fraser/research/2004ukindustry-byindustryanalyticalinput-outputtables/

We adopt the usual calibration method for the model that involves agents with perfect foresight[13]. The benchmark value of W corresponds to the discounted flow of current income, NFW to the discounted flow of net labour income, and FW is obtained by maintaining asset equilibrium. For all sectors, trade elasticities are set equal to 2 (Gibson, 1990) whilst production elasticities are equal to 0.3 (Harris, 1989). The values of the adjustment cost parameter in the investment function, z is assigned a value of 1.5. The interest rate is set to 0.05 (which is faced by producers, consumers and investors), the rate of depreciation to 0.1 and with constant elasticity of marginal utility equal to 0.8. In the benchmark equilibrium the price of capital goods, Pk, is set to unity since the benchmark prices on the consumption side are set equal to one.

The degree of habit persistence (b) in consumption is set to 0.8 for both internal and external habit (see Banerjee and Batini, 2003; Batini *et al*, 2003)

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

The value of the elasticity of substitution and the correspondent price elasticity of energy services might vary widely according to type of energy services (such as personal transportation, residential space heating or cooling). However, in the CGE model we do not distinguish between different types of energy services, so that the price elasticity estimated is for the demand of energy services as whole. Indeed, our purpose is not confined to a partial equilibrium analysis but it aims to obtain a measure of the potential magnitude of the economy-wide rebound effects by using the estimated elasticity into the CGE model.

From eq. (3) we derive the first order conditions. Taking logs and rearranging, gives:

[13] See Lecca *et al* (2010) for a detailed discussion of the process of calibration of the intertemporal variant of the AMOS CGE modelling framework.

$$\ln\left[\frac{C_{(NE),t}}{C_{(E),t}}\right] = \beta_0 + \beta_1 \ln\left[\frac{P_{(E),t}}{P_{(NE),t}}\right] + \mu_t, \qquad (10)$$

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. However, the model we choose to estimate, common in the empirical literature, is the following:

$$\ln\left[\frac{C_{(NE),t}}{C_{(E),t}}\right] = \beta_0 + \beta_1 \ln\left[\frac{P_{(E),t}}{P_{(NE),t}}\right] + \beta_2 \ln\left[\frac{C_{(NE),t-1}}{C_{(E),t-1}}\right] + \mu_t, \qquad (11)$$

From the specification of the model as an autoregressive model of order one (AR(1)) we can define the short and long-run elasticity of substitution. The former is given by β_1 and the latter is obtained as $\beta_1/(1-\beta_2)$ for $0 < \beta_2 < 1$.

Data on $C^{H}_{(E),t}$, $C^{H}_{(NE),t}$ $P^{H}_{(E),t}$ and $P^{H}_{(NE),t}$ are required and are shown in Figure A1 in Appendix I. We use quarterly data from 1989:1 to 2009:3. The energy index price is obtained from the Economic and Social Data Services (ESDS) database[14] while all the other are from the UK Office for National Statistical (ONS)[15].

The overall consumer price index is used as a proxy for the non-energy price index.

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

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

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. Results of the parameter estimations and the associated confidence intervals are reported in Table 1. The GME confidence intervals are obtained through bootstrap method. Re-sampling has involved 1000 simulations. More detail about GME estimation is given in Appendix II.

Table 1

OLS and GME estimations

				95% confidence interval			
Estimation	OLS	GME		OLS		GME	
	Est.	*Est.*		*low*	*high*	*low*	*high*
β_0	0.52	0.53		0.10	0.93	0.52	0.57
β_1	0.10	0.10		0.01	0.19	0.00	0.14
β_2	0.86	0.85		0.74	0.97	0.72	0.90

For the OLS estimation the R^2=0.681; *DW*: 1.94; Reset test F(2,33): 1.3797 [0.2658]; Normality test: $\chi^2(2)$: 2.5 [0.2865]

According to the results summurized in Table 1 the GME and OLS estimations yield to identical results. The short and long-run results for ε equal to 0.1 and 0.67 respectively. [16]. By and large, our estimates are in line with previous empirical evidence. for the UK households (see e.g. Baker and Blundell, 1991 and Baker *et al*, 1989) which predicts price elasticity generally less than one, meaning that backfire effects are unlikely to occur at least for the case of household rebound.

The 95% confidence interval for the elasticity of substitution derived from the GME and OLS estimations are 0 - 0.14, and 0 - 0.19, respectively. For both models the width of the confidence interval is small and the lower boundaries identify a Leontief relationship. The confidence intervals from the GME estimation are then used to carry out a sensitivity analysis to determine the potential range of the households and economy-wide rebound effects (see Section 9).

[16] A comprehensive review of empirical estimates of direct rebound effects is in Sorrel *et al*, 2009.

The sample share of energy consumption in total consumption is 3.6%, which means that the price elasticity of energy demand is -0.096 and -0.646 in the short and long-run, respectively. These elasticities provide also a measure of the direct rebound effects of 9.6% in the short run and 64.6% in the long run[17].

There are a numbers of empirical studies that uses econometric analysis to estimates the direct rebound effects of different types of energy servises demand by household. Most of these are mainly for US. For example, for the case of household heating estimates varies in the range 10%-60% and in between 4%-26% for the case of space cooling

4. Model solution and simulation strategy

In all simulations presented in this paper, we introduce a costless permanent step increase of 5% in energy efficiency in household consumption. We report results for two conceptual time periods, the short run and the long run, and the multi-period impact. The short-run impact corresponds to the first period of the simulation where we impose capacity constraints. That is to say, capital stock is fixed, not just in total but also its sectoral composition in this time interval. However, from the second period capital stock adjusts through investment and depreciation. In the long-run the state variables of the model are subject to trasversality conditions, so as to obtain a new steady state.

As summarized in the Table 2, we can distinguish 4 scenarios: **1**, **2**, **3**, **4**. Only in Scenario **1**, the short-run and long-run impacts are obtained using the short-run and long-run household demand elasticity respectively. In all, the others we use only one elasticity of substitutions, namely the long-

[17] We consider the estimated elasticity of energy demand as a proxy of the direct rebound effects (Khazzoom, 1980). This is of course the easiest and more straightforward definition of direct rebound that we are aware to be subject to bias (Sorrell and Dimitropoulos, 2008).

run one. The Scenario **3**, refer to the case where the model is run adjusting the *cpi*, according to EQ. (9) while habit persistence are introduced only in Scenario **4**.

Table 2

Description of the simulations

Scenarios	**1**	**2**	**3**	**4**
Elasticity of substitution between energy and non energy in household consumption	$\varepsilon_{SR} = 0.1$ $\varepsilon_{LR} = 0.7$	$\varepsilon_{SR} = 0.7$ $\varepsilon_{LR} = 0.7$	$\varepsilon_{LR} = 0.7$	$\varepsilon_{SR} = 0.7$ $\varepsilon_{LR} = 0.7$
Adjusted *cpi*	NO	NO	YES	NO
Habit persistence	NO	NO	NO	YES

In Table 3 we report the short and long-run impact on key macroeconomic variables in terms of the percentage change from the initial values[18]. We begin with scenario 1 where we impose the conventional utility function. In the first two columns we report the short-run and long-run impact of energy efficiency improvement in the household sectors using the corresponding estimated elasticities of substitutions: 0.1 and 0.7 respectively. The third column shows the long run impact of energy efficiency where we take into account of quality change by modifying the *cpi*.

The econometric estimation suggests that household energy demand becomes more elastic over time. This implies that households take time to fully adjust their consumption to change in energy price. There are two possible processes operating here. The first is simply that there is some informational or other type of inertia that stops households from adjusting instantaneously. The second is that the adjustment in energy demand requires investment in the household's capital goods.

[18] We run the model for 20 periods. In period one we impose capacity constraint while in the last period steady-state condition applies. So, the first period corresponds to the short-run impact and the last period gives us the long run.

Neither of these processes is endogenously incorporated in the present model. Therefore, when we report short-run and long-run results, we use short-run and long-run household demand elasticity respectively[19]. However, when period by period results are shown, the long-run elasticities are used throughout. The uses of a single elasticity of substitution for all life time also simplify the analysis of the transition path making comparison more straightforward between the cases of habit persistence and no habit.

The appropriate use of the household demand elasticities estimated raises the issue of whether consumption behaviour adjusts straight away, through the implementation of new technology, or whether there is some inertia and/or delay in adjusting habitual behaviour. For example, in the case of more energy efficient appliance, such as a fridge, while it may take time for consumers to respond and actually invest in a new appliance, once it is purchased and installed, the energy efficiency improvement take place automatically and instantly. That is, the new appliance draws less electricity to maintain a given temperature than a less efficient version. Consequently, the consumer will observe and respond to a drop in the effective price of the energy type used to run the fridge – electricity – shortly thereafter (when they receive their bill) or even instantly (if the consumer has a smart meter installed) without having to take any further action themselves. In such circumstances, it is appropriate to use the long-run elasticity from the outset (even in the short-run), where the consumer is engaged in optimising behaviour.

On the other hand, if we take an example such as the installation of loft insulation, while this will reduce the amount of energy required to heat the consumer's home to a constant temperature, the consumer has to engage in two actions: first, having the loft insulation installed, then, second, adjusting the heating control (this is in contrast to the fridge example, where the consumer only has

[19] These two time period shocks are not the results of a static simulation; these outcomes are obtained running the multi-period model imposing for all transition path one of the estimated elasticity of substitution.

install the fridge). This second stage may involve time. The consumer will have to first understand how much they should reduce their use of energy input (e.g. how much time to have the heating turned on in a given 24 hour period) and then adjust their behaviour accordingly. This may involve the consumer receiving and interpreting several heating bills and (where relevant) smart meter readings, as well as changing their behaviour in terms of how they set their heating control.

In either case, rebound will not be triggered until the efficiency improvement has taken place (i.e. the installation of new technology) *and* (consequently) the effective price of the relevant energy type has fallen.

4.2. Rebound Calculation

The rebound effects on the household sector, R_{HH}, and the economy wide rebound effects, R, arises when the improvement in efficiency is partially (or totally) offset by an increase in energy consumption. They are defined as follows:

$$R_{HH} = \left[1 + \frac{\dot{E}_{HH}}{\rho}\right] \times 100 \text{ and } R = \left[1 + \frac{\dot{E}_{T}}{\alpha\rho}\right] \times 100$$

where ρ is the value of the energy efficiency improvement, $\dot{E}_{HH}$ and $\dot{E}_{T}$ are the percentage change variations of energy consumption respectively in the household sector and all domestic transactors, and α is the share of energy use directly affected[20].

R_{HH} (R) is negative if reduction in energy consumption is greater than the change in efficiency. While R_{HH} (or direct rebound) is just related to household energy consumption, the magnitude of the economy-wide rebound depends in actual fact on the impact that an improvement in energy

[20] That is to say, the household energy use/the total domestic energy use, which includes the use of energy domestically produced and imported from the RUK and ROW.

efficiency in the household sector has not only in the final use of energy (final demand) but also use by the industrial sectors (intermediate demands).

5. Discussion of the results

5.1 Scenario 1

We begin by considering the short-run results in column one of Table 3. This is where the elasticity of substitution is low and capital stock is fixed. Energy saving in the household sector is 4.06% while the energy consumption price falls by 0.55%. However, the reduction in consumption is partially offset by a 1.31% increase in exports generated by the increase in competitiveness. As the demand for energy falls so do energy firms' profit expectations. This is reflected in the decline in the real shadow price of capital by 0.85% in turn reducing investment by 4.29%. On the other hand, the relatively low sensitivity to price changes encourages consumption in commodities other than energy. Although the demand for energy falls, the overall level of economic activity rises. Output, consumption and investment increase respectively of 0.03%, 0.16% and 0.35%. This stimulates labour demand, lowering the unemployment rate by 0.27% increasing, as a consequence, the bargaining power of workers producing a rise in the real wage of 0.03%.

In the long-run, investment and output in energy sector are still below the base year values and capital stock and employment, in this sector fall by 0.48% and 0.50% respectively. Note also that in the long run, the reduction in energy output is even less than in the short run. Indeed the downward adjustment in the capital stock makes the fall in energy output greater. GDP increases by 0.1% while exports decrease in all sectors, including the energy sector. The overall level of employment, investment and consumption rise the 0.09%, 0.10% and 0.26% respectively from their base-year values. This means that expansion in economic activities is mainly driven by the increased household consumption of non-energy sector. This improvement in efficiency has the effect of changing the composition of consumption shifting household consumption toward non-energy goods and services. The shift in consumption raises economic activities putting upward pressure on real wage which in turn cause the fall in competitiveness and thus an increase in commodity prices in all sectors.

There is a -0.48% contraction in capital stock in the UK energy sector. In all other UK production sectors there is a long-run increase in capital stock in response to the demand stimulus provided by the increase in household energy efficiency and this is reflected in the net increase in aggregate investment. In order to restore equilibrium in the capital market, the drop in the price of UK energy dissipates over time, allowing the shadow price of capital to rise to equilibrate with the replacement cost of capital (so that Tobin's q equals 1) in the long run. This constrains the magnitude of the long-run rebound effect (see Turner, 2009).

In long-run the price of energy rise contrasts with what we would expect if energy efficiency were applied to the production side of the economy. As against an increase in efficiency in production, a household energy efficiency shock is confined to the demand side of the economy and the supply side of the economy is only indirectly affected through the disinvestment effect in the energy sector. For instance, an increase in efficiency in the industrial use of energy would reduce the price of energy, measured in efficiency units, which in turn tend to lower the price of output (and commodities) not only in the energy sector. This stimulates competitiveness and in turn economic activity.

The reason for this price behaviour is that the energy efficiency provides an expansionary shift only in the non-energy demand which is composed of sectors with high labour intensity. Thus, the increased demand for non-energy good and services increases the demand for labour which reduces unemployment, stimulates the real wage and therefore prices. There is also an incentive to increase capacity in these sectors. In contrast, for the energy sector the reduced demand initially generates a fall in the price due to a fall in the capital rental rate, which causes disinvestment in the energy sector. Yet, because we are dealing with a unified labour market where the wage rate does not vary across sectors, the actual energy price rises in the long run. In the other sectors, prices rise in the long run but less than the short run due to the adjustment process of capital accumulation.

The decrease in energy output of 1.10% in the short run is accompanied to a reduction in the final demand of energy and in the demand for energy from industrial sectors of 3.69% and 0.29% respectively. In the long run energy output falls by 0.48% and the total energy demanded by industries and by the final demand decrease by 0.13% and 1.21% respectively. This implies that the household direct rebound and the economy-wide rebound are bigger in the long-run than the short-run. This result is consistent with the argument presented in Wei (2007) and Saunders (2008) that rebound effects will always be lower in the short run than in the long run. Wei (2007) and Saunders (2008) point out that rebounds effect are constrained in the short run because factor of production are fixed in this time frame. However, in the long run as capital accumulates with investment there will be a further expansion that would allow rebound effects to grow. Both authors consider an efficiency improvement in production, while in this paper we are dealing with efficiency in energy efficiency in consumption. So that, here the main source that constraint rebound effects in the short-run is the lower short run elasticity of substitution used to obtain the short-run impact. In fact, when we apply the same elasticity of substitution to obtain both the short and the long-run impact the argument put forward by Wei and Saunders does not hold.

5.2. Scenario 2.

In the third column of Table 3 we show the short-run impact obtained by imposing the long-run elasticity of substitution between energy and non energy. With a greater elasticity the shift toward non-energy goods and the reduction in energy consumption is lower than the short-run reported in the first column. Therefore, it is not surprising to find that the aggregate level of output, employment, and investment is lower when the model is run with the long-run elasticity value.

The energy price behaviour is the same analysed above. Figure 2 reports the percentage change in sector prices for the whole period of adjustment up to the attainment of the new steady state. The shock not only fails to generate a persistent price reduction in the energy sector (this price fall only in the first periods) but also the prices in all non-energy sectors rise during the entire transition path[21].

Since the elasticity of substitution between energy and non-energy is still less than one for each group of households, gains from the increased efficiency are not totally exhausted by increases in demand for energy services via rebound effects. Despite the fall in energy price in the short-run due to the 5% increase in energy efficiency, the consumption of energy in the household sector falls. In the long run the price rise and the household consumption of energy falls by slightly more. These results, suggest that the overall household rebound effect in the aggregate household sector is bigger in the short-run (74.7%) than the long-run (73.4%).

In the base year, household energy consumption is about 32% of the total energy use (includes intermediate and final use of energy, excluding exports, both domestically supplied and imported). This also means that energy consumption in household sector has to some extent a relatively large impact in identifying the economy-wide rebound effect. Total domestic energy use falls in the

[21] However this result only holds if the labour force is fixed. If we allow labour supply to adjust through migration using e.g., the net migration function commonly employed in AMOS (McGregor *et al*, 1996), in the long run the real wage and therefore also prices, return to their pre-shock level. That is to say, we should obtain typical Leontief results where only quantity changes but prices are invariant.

short-run by 0.46% and in the long-run by 0.53%. Thus, the economy-wide rebound is greater in the short-run (71.9%) than the long-run (67.2%).

5.3. Rebound effects and disinvestment effects

For an increase in efficiency in the use of energy in production Turner (2009) identifies the presence of disinvestment as a necessary but not sufficient condition for the rebound value to be greater in the short-run than in the long run[22]. We identify such "perverse" effects where the key elasticity parameter is the same for the entire transition path.

In Figure 3 we plot the shadow price of capital for each sectors and the replacement cost of capital. The curve of the shadow price of capital for energy sector is above the curve of the replacement cost of capital for the entire adjustment path (implying that Tobin's q<1). Ultimately, there is complete adjustment where the capital stock reaches the steady state equilibrium. The trigger for the disinvestment effect can also be observed in the short-run results where the shadow price of capital falls by 0.23% in the UK energy sector. This is the trigger for shedding of capital stock in the energy sector. The shadow price of capital falls because the initial contraction in demand for energy sector output, due to energy saving in the household sector (the pure efficiency effect) causes the price of this output to fall. We should also note that apart from manufacturing, in all the other there is a stimulus to investment.

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As in Turner (2009), it is the disinvestments effect, that constraint the long-run rebound effect. In our analysis, however, we find that the disinvestment is not the only element that limits the long-run

[22] Such a result contradicts the theoretical prediction of Saunders (2008), who argues that general equilibrium rebound effects will always be bigger in the long-run due to general expansion in economic activity when efficiency in the use of energy increases. However, as Turner (2009) explains, Saunders (2008) prediction is based on the theoretical model of Wei (2007), where the return on capital is assumed fixed and exogenous.

expansionary effect making long-run rebound lower than the short-run. Loss in competitiveness in the energy sectors, which is partially driven by disinvestment effects,

is another factor that constraints both the economy-wide and the household long run rebound effect. In Turner (2009) the analysis was confined to the supply side of the economy where energy efficiency occurs in the industrial use of energy. In that case export was stimulated by an increase in efficiency that in turn lowers the domestic price of energy and non energy goods.

Indeed, in our analysis we find that both the economy-wide and household rebound effects are bigger in the short run than the long run when both the short-run and the long-run impact are obtained by using the same elasticity of substitution between energy and non energy (in this case $\varepsilon_{LR} = 0.67$). But, the long run rebound is greater in the long-run than the short-run if the short-run impact is obtained using its own elasticity of substitution ($\varepsilon_{SR} = 0.1$). Although in both simulations we observe disinvestment in the energy sector, where the demand is more elastic in the long run, we obtain conventional results, where the short-run is lower than the long-run rebound. However, if the demand elasticity does not change over time, then if disinvestments occur, there will also be a larger short-run than long-run rebound. This finding, certainly hold in partial equilibrium analysis as shown in Allan *et al*., (2009) and in previous numerical general equilibrium analysis (Allan *et al*., 2006; Hanley *et al*. 2006, Turner, 2009).

The appropriate use of the elasticities of substitution makes the difference in the calculation of the rebound. We have calculated the impact of energy efficiency for two conceptual time frames and for the entire transition path. By and large it is widely accepted that for a one period (or temporary) shock, the short-run elasticity should be the more appropriate to use, given that individuals will be less responsive to price change when energy efficiency policies are introduced. However, in order to obtain the long-run impact, a greater level of price responsiveness is required. For a permanent shock, since the interest is to study the entire transition path towards a new long-run steady-state equilibrium, the long run elasticity is the appropriate one to use[23].

6. Results of energy efficiency for the case of adjusted cpi: Scenario 3

What we have seen in the previous sections is that where energy demand is inelastic, increased energy efficiency produces a positive demand shift towards non energy sectors and conversely the household demand for energy measured in natural unit falls. Our assumptions up to this point imply that changes in energy efficiency in the household sector act in the same way as change in tastes. They simply modify the allocation of energy and non-energy goods and services within each period according to the elasticity of substitution between energy and non energy good and services in the household sector.

At present the real wage has been expressed as a function of the nominal wage and *cpi*, which combines the price of energy plus non-energy commodities, measured in natural units. However, in defining the *cpi* it is more appropriate to measure the energy price in efficiency unity. The real wage is then calculated as describe in Eq. (8) and Eq. (9) above. In so far, as improvements in energy efficiency reduce the energy price, measured in efficiency units, then this can be a source of improved competitiveness as the nominal wage falls.

Thus, in this section, we consider the case in which a change in efficiency in the household sector provides not only a change in tastes but also an increase in the quality of energy services that is reflected in the real wage adjustment. In order to keep the comparison as simple as possible, we carry on the analysis of a 5% increase in energy efficiency in household consumption. The elasticity

[23] A one period shock with long-run closures produce the same equilibrium of a permanent multi-period shock of the same magnitude.

of substitution is set equal to 0.7 for all periods and consumer preferences are expressed by the conventional utility function that is, with no habit persistence.

In Figure 4 we compare the period by period adjustment of the *cpi* and nominal wage with the Scenario 2. We see that in the Scenario 2 both the *cpi* and the nominal wage are above their base year values. However, in the simulation where we account for the fall in the price of energy in efficiency units, both *cpi* and nominal wage are below the base year values. The fall in nominal wage encourage economic activity so that there is a greater impact on key macroeconomic variables such as GDP, employment and investment with respect to the Scenario 2 (see last column of Table 3).

In the long run, although the real wage rises, the nominal wage falls. This generates price reductions in all production sectors. This is in contrast to the results in the preceding sections. The fall in *cpi* and consequently the reduction in the labour cost are passed through to lower prices. The dynamic of the commodities price, reported in Figure 5, is significantly different from that shown in Figure 2. For the energy sector, the price is constantly below its base year level and the price adjustments in the non energy sectors are quite different. In all of the non energy sectors the commodity price actually falls in the long run after increasing in the initial periods of transition. The drop in prices improves competitiveness in the energy sector in both the short and long run, though exports increase only in the long run for all the other non-energy sectors.

Similarly to the previous case, reduction in the demand for energy services (measured in physical units) leads to fall in the shadow price of capital such that the price reduction over the entire time interval causes disinvestment in the energy sector which is greater in the short run than the long run.

The figures for the households and economy-wide rebound are respectively 74.07% and 73.8% which are slightly higher than the corresponding central case figures, meaning that the overall expansion of the economy and a fall in the price of energy in the long run generates additional final demand energy use.

7. Results of modelling agents with habit formation: Scenario 4

In this section, we examine whether the introduction of habit persistence in consumption is sufficient to change the composition of household consumption in order to modify the extent of household rebound. Furthermore, in considering different specifications of habit (internal and external) we consider whether qualitative and quantitative differences arise with respect to the Scenario 2 and analyzing how habit formation influences the impact of an increase in energy efficiency on the evolution of the economy.

For all three models we make the assumption that within period the shape of the relationship between energy and non energy goods and services is defined by the same elasticity of substitution, ε=0.7, as in Scenario2, for the entire transition path. This simplifies the analysis significantly. The application of the short-run elasticity for the first period only quantitatively impacts the results, but as the sensitivity analysis confirms, the qualitative results emphasized in this paper, especially in this section, depend only on the specification adopted for the utility function.

In Figure 6, we report the period by period percentage changes of aggregate consumption for the central case model (no habit) and the cases with internal and external habit formation. We see that consumption growth is different during the transition path but ultimately all three curves come to rest at the same steady-state equilibrium. The differences are all in the adjustment path towards the long-run equilibrium. From the chart, it is clear that households having conventional preferences enjoy bigger short-run consumption increases than those having non- time separable preferences. This is because with habit preferences, consumers try to maintain their previous standard of living and in that case after the increase in efficiency agents will substitute future for present consumption, by in this case, increasing saving.

For the case of external habit, and despite heterogeneity in the household sector, we see that the transition path is similar to that of internal habit. So, in the short run, in terms of aggregate consumption, an external or internal habit does not make significant differences. Aggregate consumption increases by 0.051% and 0.052%, with respect base year value, for internal and external habit respectively which are less than half if compared to the change for the case of no-habit.

One very small difference occurs between the two time non-separable model specifications. This is because with the external habit, each household's habit is determined by average consumption in the economy as a whole rather than by the average consumption of their own group. Thus a switch from internal to external habit formation does not make much impact on aggregate consumption. This point has also been made by Campbell and Cochrane (1999, pg. 245) where different habit specifications are analysed in order to identify asset price behaviour.

The exogenous efficiency shock implies changes in the quantitative sectoral composition of household consumption when we switch from the no-habit to the case of habit persistence. The simulation results suggest that the household energy requirement is different for the three model specifications. Total energy saving in the household sector is 1.39% for the case of internal habit but rest to 1.42% when we impose the external habit. So, in the short-run the household rebound effects are bigger for the case of no-habit and lower for the case of external habit.

In the long run, and regardless of the agents' behaviours, energy consumption falls in each households group with upper income classes that save more energy than lower income households. Table 4 shows that rebound effects are in the order of 75.9% for the lowest income quintile and 72.5% for the highest one. This occurs because we are assuming a fixed population and the number of households remain unchanged, and the wage rate together with the price of energy does not change across households so that more energy-intensive households save proportionately less energy.

While in the long run the household rebound effect remains unchanged between the three different models, in the short run the greater consumption smoothing for the case of habit persistence produce differences in energy saving across households. Table 4 reveals that in the short run for the case of internal habit and conventionally determined household consumption, the energy saving for each group of households has the same long-run order, namely, household rebound effects are bigger for lower income households. However, this is not the case when agents have time non separable preferences in the form of external habit. Here rebound effects are higher for upper income quintiles: for the poorest household the rebound effect is 66.6% while for the richest one is 73.5%.

According to the model configuration, once each household makes intertemporal decisions of the aggregate level of consumption and saving, then within period they allocate consumption to energy and non energy good and services. Since the elasticity of substitution, which defines the magnitude of the rebound, is the same across the board and for the three model specifications, it is the aggregate level of consumption that produces different magnitude for household rebound. For the case of external habit formation, households' current utility depends upon the average household's aggregate past consumption, rather than individual consumption. Thus, there will be some households whose level of consumption is below the average and other well positioned above the average. Now if we look at the Figure 7 we see that the extent to which household smooth consumption is greater for a group of household with level of consumption below the average household consumption (e.g. the poorest one) and vice versa. The level of aggregate consumption for the first and second quintile is even negative, implying that they are saving a bit more than other households. Poorer households are consuming less overall, then they will consume less energy as well. This implies that, in the short run, and under external habit, the income effect is proportionately lower for poorer household. This also means that, contrary to the internal and no habit case the reference benchmark energy-intensities do not play a significant role in defining consumers' decisions.

8. Sensitivity analysis: changing the elasticity of substitution

In this section we calculate the magnitude of the household and economy-wide rebound effects for the range of the elasticity of substitution we have found in Section 4. For a 95% confidence interval the elasticity of substitution between energy and non-energy in the household sector fall in the range $0 < \varepsilon < 0.14$ in the short run and $0.01 < \varepsilon < 1.38$ for the long run.

The simulations carried out here and the corresponding rebound effects reported in Table 5 are the results of running the model with the conventional time separable utility function where the short run and long-run rebounds are obtaining applying the short and long run elasticities respectively.

Our sensitivity analysis predicts a very large range for the rebound effect for the long run. However the range is tighter for the short run. This is due to our long-run estimate confidence interval where the lowest level of the long-run elasticity of substitution is almost a Leontief while the highest prediction is above the Cobb-Douglas relationship. The long run household rebound fall in between 10.3% and 142.6% while the economy-wide rebound rests between -15.5% and 157.8%.

The short run economy-wide rebounds are all negative, when the elasticity of substitution is set to its low level, meaning that the overall energy use (intermediate + final demand) fall more than the change in energy efficiency. One more thing worth notiing is that in the case of external habit for the first income quintile we have negative rebound effects.

9. Conclusions

The impact of energy efficiency improvement has commonly been analysed on the production side of the economy, at least in a CGE modelling framework. The main contribution of this paper is to study the impact of energy efficiency improvement in the use of energy in household consumption and show the resulting economy-wide and household rebound figures.

Initially we have estimated the elasticity of substitution between energy and non energy in household consumption. As expected, demand is more elastic in the short than the long run. Two interesting findings can be observed from the simulation results. First, when we use the long-run elasticity to obtain both the short and long-run impacts, rebounds are lower in the long-run than the short-run. This is the case already identified in previous works using computable general equilibrium models (Allan *et al*., 2006; Hanley *et al*., 2007, Turner, 2009) and in the partial equilibrium context (Allan *et al*., 2010). Second, when the short and the long-run impacts are obtained using the short and the long-run elasticity respectively, rebounds are lower in the short-run than the long run although the presence of disinvestments. This result is instead consistent with previous analytical works (Saunders, 2008; Wei, 2007 and 2010).

Given that households consider the price of energy as given, only when we adjust the *cpi* and the real wage for reductions in the price of energy in efficiency units does the price of energy fall for all the transition path. In our central scenario the increase in efficiency acts as a modification of tastes, changing, as a result, the composition of household consumption. However, when households internalize the efficiency, the *cpi* adjusts in a way to put downward pressure on nominal wage, and thus on prices. The long-run demand for energy decreases more in the central case scenario, where the price of energy rises than the case in which we adjust the *cpi*, where the price of energy falls. The reason for this is due to the greater output effect yielded when energy price is expressed in efficiency units in the *cpi* equation, driven by a fall in nominal wage and prices which increase the foreign demand for local goods, stimulating further economic activity.

One more issue we analyse here is the extent to which the introduction of habit formations might change the composition of household consumption in order to modify the magnitude of the household rebound. First, we have seen that in the long run the impact is the same, no matter the type of habits persistence introduced in the model. This is because the introduction of habit has only implication for the speed of convergence towards the new equilibrium. However, the short run is different for both the aggregate level of energy consumption and for the five income quintile specified in the model.

It can be seen that, household and economy-wide rebound are lowest for external habit formation and highest when consumers' preferences are defined using a conventional utility function. Furthermore, for the case of external habit persistence, rebound is lowest for the poorest households whilst the percentage of energy savings in richest household is less than in the poorest.

The sensitivity analysis shows that only in the short-run the width of the potential rebound interval is small. However, there is greater uncertainty in the long-run where the calculated rebound values falls within a large range.

In this analysis we have considered a collection of energy services, without distinction between different types of services. We would expect for example, heating and refrigeration to have different own price elasticities, which means different rebound effects. Furthermore, we have just considered the case in which energy services can be substitute with a single aggregate of goods and services. However, it might be the case to have different elasticity of substitutions between energy services and consumption of goods and services from one side and energy and durable goods to the other side.

Table 3

Short run and long run impact on key macroeconomic variables of a costless 5% increase in energy efficiency in the Household sector. Percentage change from the initial steady state.

	Scenario 1		Scenario 2	Scenario 3
Elasticity of substitutions	ε_{SR}	ε_{LR}	ε_{LR}	ε_{LR}
	SR	**LR**	**SR**	**LR**
GRP Income measure	0.03	0.10	0.02	0.21
Consumer Price Index	0.13	0.05	0.12	-0.03
Unemployment Rate	-0.27	-0.51	-0.18	-1.24
Total Employment	0.05	0.09	0.03	0.22
Nominal Gross Wage	0.17	0.11	0.14	-0.07
Real Gross Wage	0.03	0.06	0.02	-0.04
Households Consumption	0.16	0.26	0.17	0.30
Investment	0.35	0.10	0.20	0.19
Non Energy output	0.05	0.10	0.03	0.22
Household rebound	18.80	73.36	74.71	74.07
Economy wide rebound	11.29	67.16	71.92	73.88
Energy sector*				
Capital Stock	0.00	-0.48	0.00	-0.36
Employment	-1.32	-0.50	-0.44	-0.35
Energy output	-1.10	-0.48	-0.36	-0.36
Household consumption of energy	-4.06	-1.33	-1.26	-1.30
Total domestic energy use	-1.44	-0.53	-0.46	-0.42
T.Energy demand by industries	-0.29	-0.13	-0.09	-0.01
Energy Final demand	-3.69	-1.21	-1.14	-1.17
Shadow price of Capital.	-0.85	0.05	-0.23	-0.03
Commodity price	-0.55	0.05	-0.12	-0.03
Export				
Primary	-0.43	-0.12	-0.32	0.08
Manufacturing	-0.35	-0.19	-0.29	0.12
Construction	-0.49	-0.13	-0.40	0.08
Services	-0.44	-0.15	-0.35	0.10
Public servises	-0.45	-0.15	-0.35	0.10
Energy	1.31	-0.13	0.29	0.08
Investment				
Primary	0.61	0.16	0.30	0.29
Manufacturing	0.14	0.01	-0.32	0.22
Construction	0.14	0.05	0.19	0.14
Services	0.76	0.20	0.45	0.29
Public servises	0.47	0.12	0.26	0.19
Energy	-4.29	-0.48	-1.48	-0.36

Table 4

Short run and long run household and economy-wide rebound resulting from a costless 5% increase in energy efficiency in the Household sector.

	Short-run impact						Long-run
	ε=0.7			ε=0.1			
	No-habit	Internal	External	No-habit	Internal	External	
Economy-wide rebound	71.92	69.50	68.69	11.29	8.97	7.99	67.16
HH rebound	74.71	72.18	71.59	18.80	16.35	15.60	73.36
HG1	77.33	72.61	66.63	25.83	20.96	14.52	75.85
HG2	75.42	72.28	70.15	23.73	20.57	18.34	74.01
HG3	74.55	72.14	71.91	22.73	20.39	20.11	73.20
HG4	74.06	72.07	72.78	22.13	20.29	20.92	72.75
HG5	73.73	72.03	73.52	21.73	20.22	21.57	72.45

Table 5

Sensitivity analysis

	Short-run impact						Long-run	
Elasticity	**Low**			**High**			**Low**	**High**
	No-habit	Internal	External	No-habit	Internal	External		
Economy-wide rebound	-0.17	-2.46	-3.47	15.72	13.39	12.43	-15.52	157.84
HH rebound	8.23	5.81	5.03	22.88	20.42	19.69	10.25	142.59
HG1	11.31	6.41	-0.14	25.83	20.96	14.52	12.66	145.17
HG2	9.14	5.98	3.74	23.73	20.57	18.34	10.87	143.27
HG3	8.09	5.77	5.48	22.73	20.39	20.11	10.10	142.42
HG4	7.45	5.65	6.26	22.13	20.29	20.92	9.66	141.95
HG5	7.02	5.57	6.88	21.73	20.22	21.57	9.37	141.64

Figure 2

Commodity prices-% change from base year values

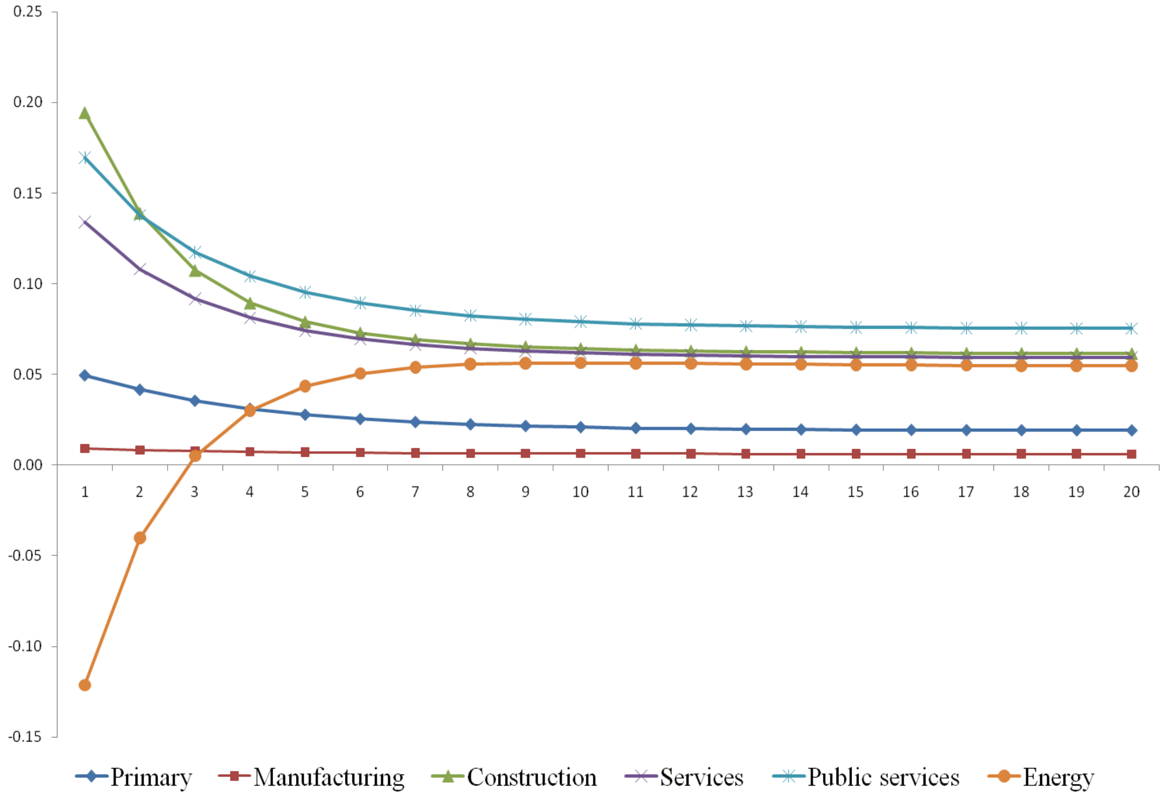


Figure 3

Disinvestment in Energy sector. Shadow prices of capital and Replacement cost of capital. % change from initial steady state.

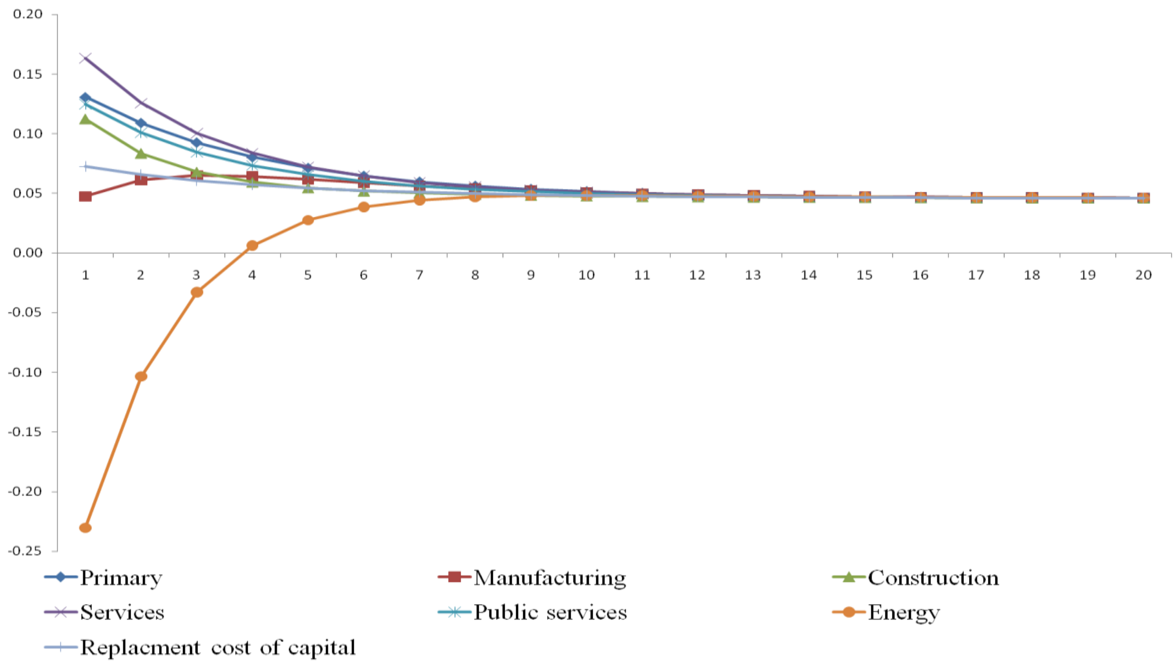


Figure 4

CPI and nominal wage. Comparison between Scenario 2 and Scenario 3

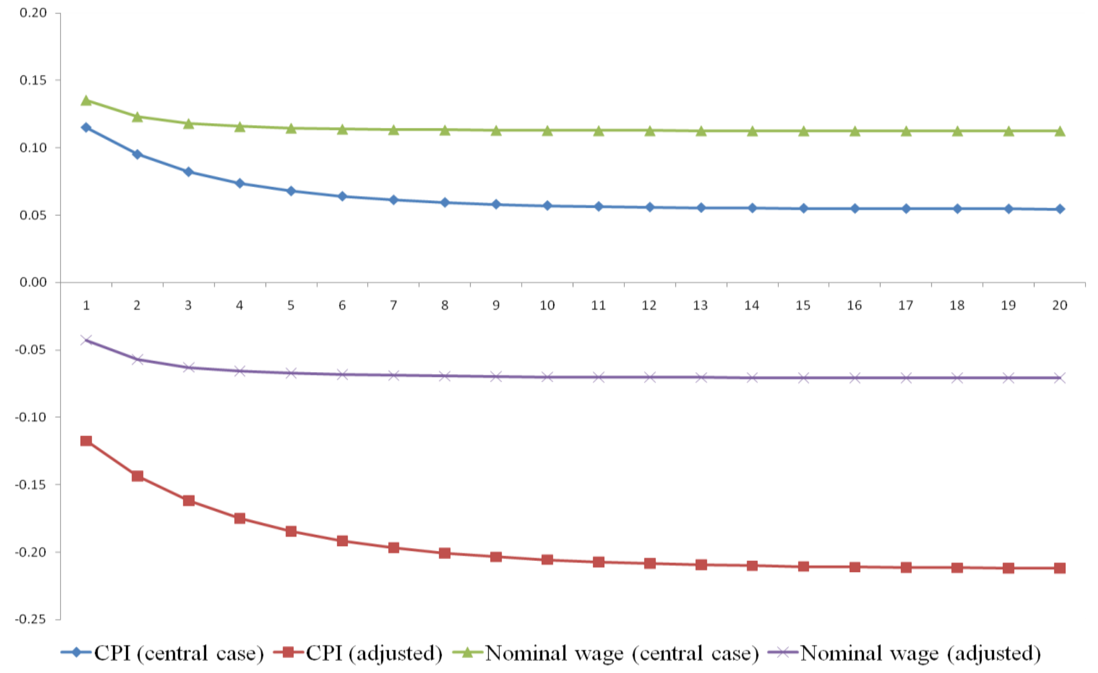


Figure 5

Commodity prices-Adjusted CPI-% change from base year values

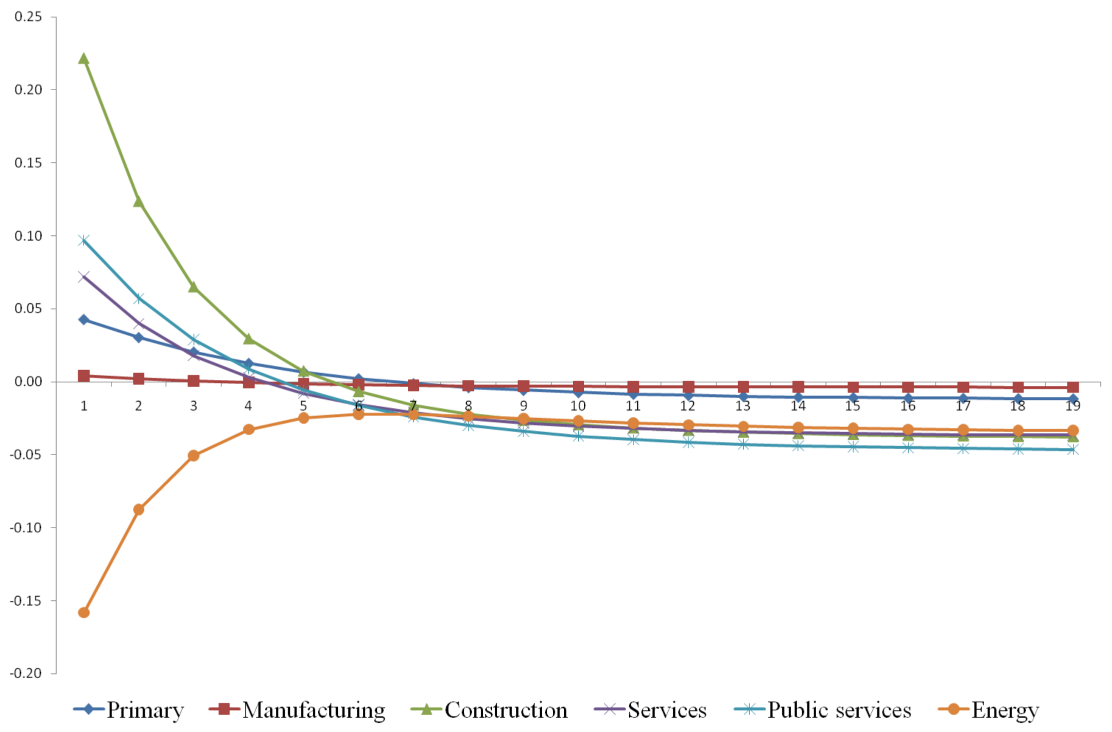


Figure 6

Period by period consumption change resulting from a costless 5% increase in energy efficiency in the Household sector.

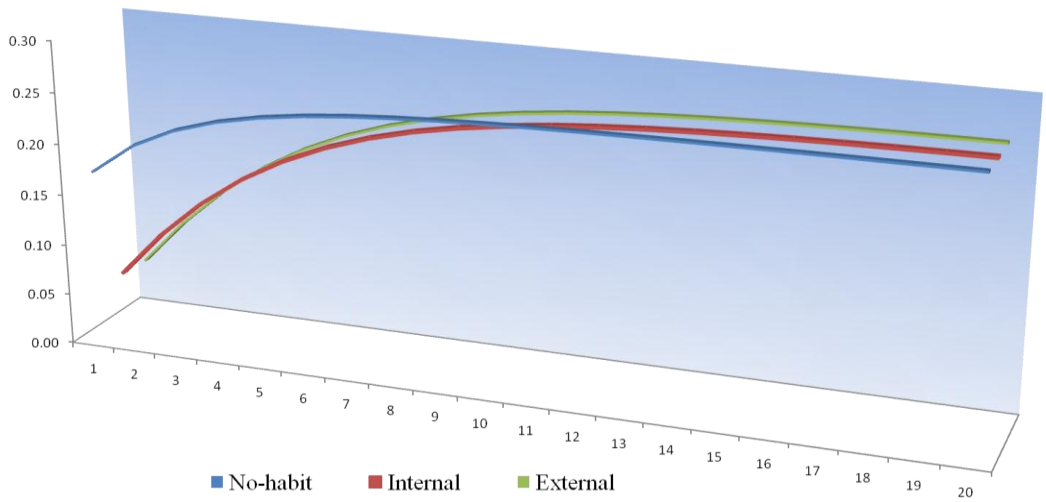
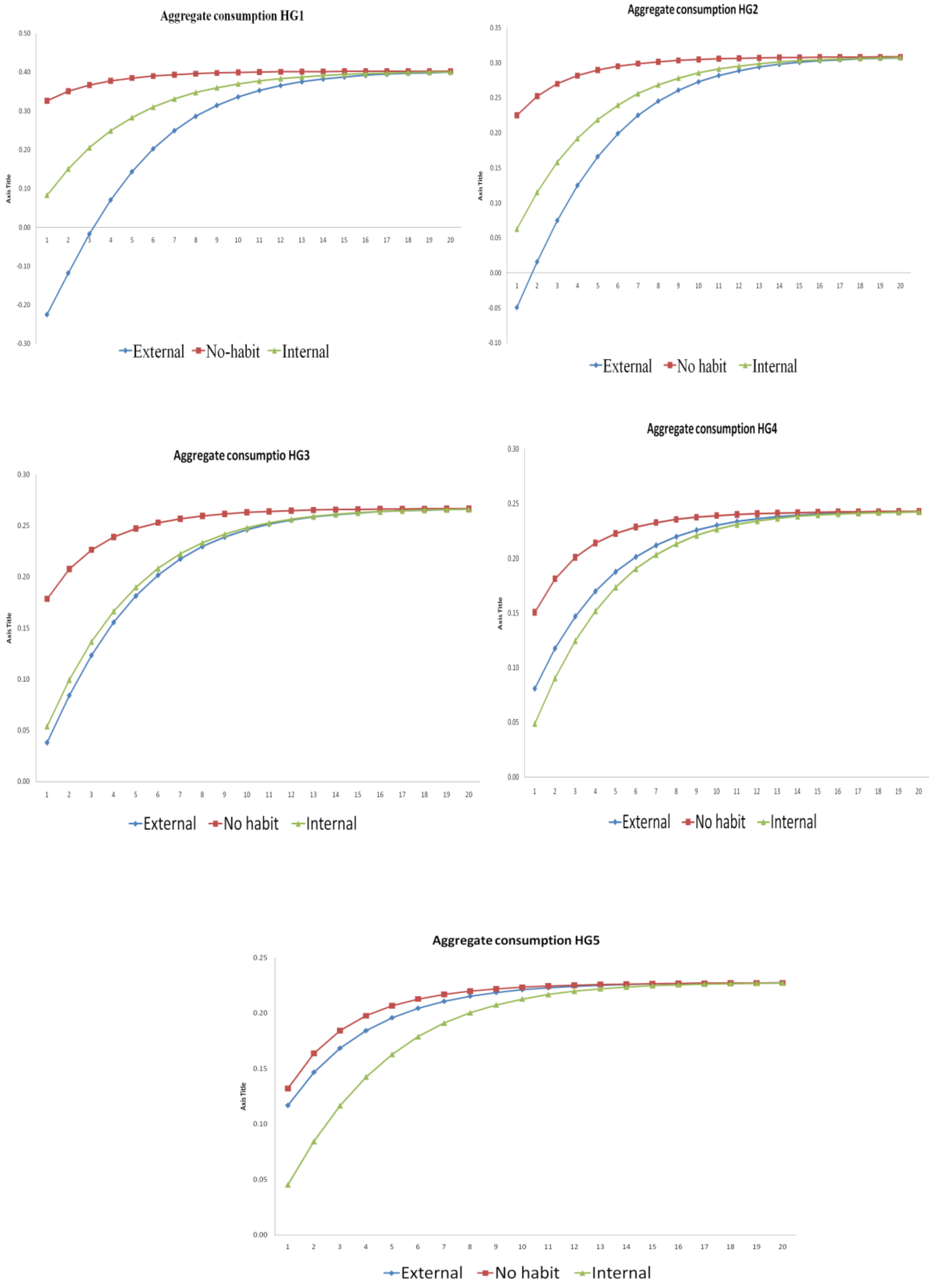


Figure 7

Period by period consumption change for each 5 income quintile and for the three specification of the utility function

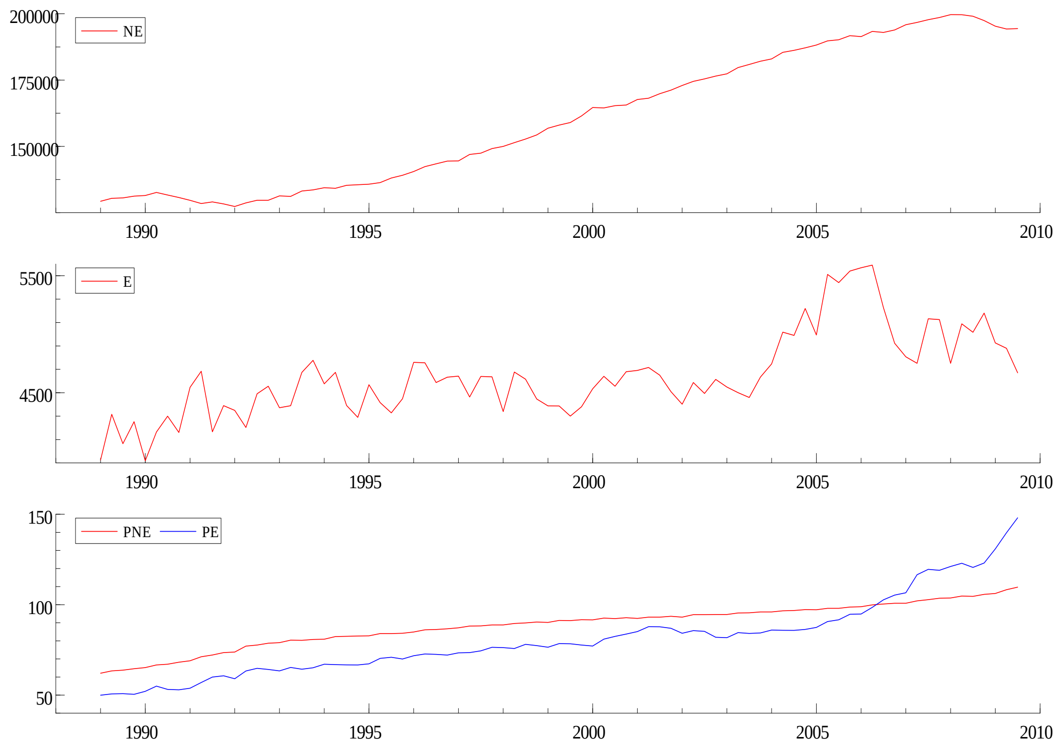


Appendix I

Table A.1

Aggregated IO Sector	Original Sector Number Included from 123 UK IO
Primary	1-3; 5-7
Manufacturing	8-84; 87
Construction	88
Retail Distribution and Transport	89-99
Other Services	100-123
Energy	4;85;86;35

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



Appendix II

The GME estimation consists to re-parameterize the linear model seen in Eq. (9). Each parameter to be estimated, β_k, (for k=1,2,3) can be parameterized as a discrete random variable with a compact support and M possible outcomes for each parameter to be estimated, $z_{k,j}$ (for j=1....M). We have the following linear system:

$$\beta_k = \sum_{j=1}^{M} z_{k,j} p_{k,j}; \qquad \text{(A.1)}$$

where $p_{k,j} \in [0,1]$ are positive weights with the property that

$$\sum_{j=1}^{M} p_{k,j} = 1. \qquad \text{(A.2)}$$

Similarly we can write a set of j support points for each error term μ

$$\mu_t = \sum_{j=1}^{M} v_{t,j} w_{t,j}; \qquad \text{(A.3)}$$

Where $w_{t,j}$ is the finite support set for the error term and $v_{t,j} \in [0,1]$ represent positive weight that sum up to one:

$$\sum_{j=1}^{M} v_{t,j} = 1; \qquad \text{(A.4)}$$

The GME problem can now be stated as:

$$Max\, H(p,w) = -\left[\sum_k \sum_j p_{k,j} \log(p_{k,j}) + \sum_i \sum_j w_{i,j}{}' \log(w_{i,j}) \right]$$

subject to Eq. (9), Eq. (A1)-Eq. (A.4). The error support is ±3σ. Prior information on σ is obtained estimating the model in Eq. (9) by OLS. The support parameter for the constant z_1=[-50, -25, 0, 25, 50] while for z_2=z_3=[-20, -10, 0, 10, 20].

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