Increased energy efficiency in Scottish households: trading-off economic benefits and energy rebound effects?

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Abstract

This paper investigates the economy-wide impacts of a 5% improvement in Scottish household energy efficiency, focussing specifically on general equilibrium energy rebound effects, both in household energy use and in total energy use across the Scottish economy. The impacts are measured through simulations using an intertemporal single region computable general equilibrium (CGE) model. Previous studies based on a national case show that improving efficiency in household energy use can stimulate the economy through an increase and change in pattern in the aggregate demand. However, this may put upward pressure on domestic prices, thereby crowding out exports. Here we find that in an open region interregional migration of workers may give additional momentum to the economic expansion, by relieving pressure on the real wage and the cpi to their baseline values and restoring the lost competitiveness. By considering different simulation scenarios we show that there is a friction between the economic stimulus from increasing household energy efficiency and the rebound effects.

1 Introduction

In the analysis of energy efficiency improvements, the rebound argument has received a deal of attention (Dimitropoulos, 2007; Jenkins et al., 2011; Sorrell, 2007; Turner, 2013; Van den Bergh, 2011). It focuses on the fact that the potential energy-saving from technologies aimed at reducing energy consumption, can be partially, or even wholly, offset by the effect of the initial energy service price reduction (Khazzoom, 1980, 1987). For this reason, it has been generally considered as an undesired consequence of increasing energy efficiency policies (Gillingham and Rapson, 2014), that needs to be taken into account when assessing the ability of such policies to decrease the demand for energy.

However, recent studies have associated the energy rebound effect with a wider range of economic benefits coming from the higher energy efficiency (Barker et al., 2007, 2009; Gillingham and Rapson, 2014; Turner, 2013). In a recent report, the International Energy Agency (IEA, 2014) argues that energy efficiency could deliver significant social and economic benefits that go beyond the traditional single objective of energy demand reduction. From an economic perspective, for example, energy efficiency has been shown to be capable of positively impacting key macroeconomic indicators, such employment, exports, and total output (Barker et al., 2007, 2009; Turner, 2009, 2013).

Computable General Equilibrium (CGE) models have often been used to investigate the economy-wide effects of energy efficiency improvements, including the rebound effect, because of of their intrinsic multi sectoral structure and whole economy characteristics (Gillingham and Rapson, 2014; Sorrell, 2007; Turner, 2013). Using CGE frameworks, studies focused on assessing rebound from energy efficiency increase in production have already underlined how a more efficient use of energy can deliver significant economic benefits. For example Allan et al. (2007) and Turner (2009) find that improving energy efficiency in production would lead to a productivity-led expansion. The findings are quite intuitive, as in these studies energy is one of the production inputs, along with capital, labour and materials. This means that improving energy efficiency will deliver similar types of effects to improving capital or labour efficiency, although with some differences, given that energy is used in smaller proportions and is a produced input.

However, macroeconomic impacts of energy efficiency have been also observed when energy efficiency increases occur in household consumption. For example Lecca et al. (2014) shows that a more efficient use of energy could lead to a reallocation of increased household expenditure towards non-energy sectors, thereby stimulating the economy through a shift in aggregate demand, but with some negative impacts on competitiveness and exports demand.

The aim of this paper is to analyse the economy-wide impacts of increasing energy efficiency in the household context, accounting both for the rebound effect and for the potential benefits of energy efficiency. We use Scotland as case study, building upon the work of Lecca et al. (2014), which focuses on the UK case. Here we use a regional Computable General Equilibrium (CGE) model for the Scottish economy to analyse the economic response of household - and of the wider economy - to an increase in household energy efficiency. We follow the approach of Lecca et al. (2014) but we focus on the regional case of Scotland. This allows us to understand some of the implications of moving from a national to a regional CGE modelling framework in the analysis of the impacts household energy efficiency improvements in the whole economy.

The rest of the paper is organised as follows. In Section 2 we define the rebound effect and review the literature In Section 3 we describe the CGE model used for this analysis. In Section 4 we illustrate the simulation Scenarios. In Section 5 and 6 we describes the results and discuss the main implications. In Section 7 we conclude.

2 The rebound effect

2.1 Direct, indirect and economy-wide rebound effect

Improving energy efficiency, whether in its industrial use or in consumption has been often associated with the rebound effect (Turner, 2013)[1]

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[1] The rebound effect has his roots in the pioneering work of Jevons (1865), who observed that increasing the efficiency of the use of coal in British industries in the XIX century could actually lead to an increase in energy demand (the so called Jevons paradox). The rebound effect has then been extended to the household context by Khazzoom (1980, 1987).

In general terms, we define the rebound effect as being the ratio between the actual energy savings (AES) obtained from increasing energy efficiency, and the potential energy savings (PES)[2], so that:

$$R = \left[1 - \frac{\text{AES}}{\text{PES}}\right] \cdot 100 \tag{1}$$

Depending on the focus of the analysis we may decompose the rebound effect in order to distinguish between direct rebound, indirect rebound and economy-wide rebound. In the literature we find several ways of defining these three types of rebound, and also different taxonomies (see for example Gillingham and Rapson, 2014; Greening et al., 2000; Sorrell, 2007; Turner, 2013). However, here we follow Lecca et al.'s (2014) approach.

The direct rebound effect occurs when an increase in energy efficiency in a specific energy service, decreases the price of delivering the service, leading to a rise in demand for the same energy service. For example following the installation of a new more efficient boiler, a household decides to heat its home for more hours per day or at a higher temperature, offsetting the expected engineering energy savings.

The indirect rebound effect may be defined in terms of re-spending of saving following a more efficient use of energy, under the assumption of fixed nominal income and prices (Lecca et al., 2014). It could involve re-spending towards other energy services, for example using the savings from a more efficient heater to drive a car more, or cook more, or towards non energy goods (clothing, leisure, etc.) produced using energy. It focuses on considering embodied use of energy in the supply chains of energy and non energy goods.

Following Lecca et al. (2014) we define the economy-wide rebound effect as including both direct and indirect rebound and also accounting for the wider set of economic impacts that occur as nominal income and prices adjust in response to the changing in demand and supply, following the initial increase in energy efficiency.

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[2] The potential energy savings correspond to engineering effect of introducing a more efficient energy technology (i.e. a 5% more efficient heater). For a different approach to considering rebound in a general equilibrium setting see Guerra and Sancho (2010) who quantify the expected energy savings in an Input-Output modelling framework in terms of quantity adjustments in the energy supply chain.

2.2 Literature

Several contributions focus on energy efficiency and rebound effect from increased of household energy efficiency (Dubin et al., 1986; Druckman et al., 2011; Frondel et al., 2008, 2012; Linn, 2013; Lin and Zeng, 2013; Schwarz and Taylor, 1995; West, 2004) [3]. A key characteristic of this literature is that the rebound effect is analysed mainly in a short-run context and it is limited to the micro level and focused on the direct rebound effect. This also means that most of the studies are based on partial equilibrium analysis, which is not able to capture the economy-wide effects of an improvement in energy efficiency.

A number of studies investigate the rebound effect in an Input-Output (IO) setting (**?**Chitnis and Sorrell, 2015; Druckman et al., 2011; Freire-González, 2011). Although the IO modelling framework can be considered a general equilibrium model, Lecca et al. (2014) explains that this cannot be considered economy-wide rebound by their definition, because of the fixed price assumption.

In a CGE framework, a number of authors have examined the economy-wide impacts of increased energy efficiency on the production/industrial side of the economy (e.g. Broberg et al., 2015; Semboja, 1994; Grepperud and Rasmussen, 2004; Glomsrd and Taoyuan, 2005; Koesler et al., 2016). Some of these studies have considered the case of UK and Scotland (see for instance Allan et al. 2007 and Turner 2009 for the UK; Anson and Turner 2009 and Hanley et al. 2009 for Scotland). However, all these works focus on efficiency improvement in production, and the economy-wide rebound effects (along with an expansionary impact on the economy) are driven by increased productivity and competitiveness.

To the best of our knowledge, few studies focus on economy-wide effects of increased household energy efficiency (Duarte et al., 2015; Dufournaud et al., 1994; Koesler, 2013; Lecca et al., 2014). Among the published work, Dufournaud et al. (1994) investigates the impact of increasing efficiency in wood stoves in the household sector in the Sudan. However, this study is quite specific to less-developed countries and cases where no energy

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[3] For extended literature reviews on the state of knowledge of rebound effect see Dimitropoulos (2007); Jenkins et al. (2011); Sorrell (2007); Turner (2013); Van den Bergh (2011)

suppliers are involved, and households provide for their own energy needs by burning wood in stoves.

Lecca et al. (2014) studies the economic impact of an across-the-board 5% improvement in the energy efficiency of UK household. They illustrate the additional insights obtained in moving from partial to full general equilibrium analysis by calibrating models with different degrees of endogeneity on a common dataset. To do this, they start from an econometric analysis of rebound, to then move to an Input-Output framework, and eventually to a full general equilibrium model with endogenous prices and income determination. On this basis, they show how it is possible to obtain a decomposition of economy-wide rebound effects into areas that may merit differential policy responses.

In Lecca et al. (2014), the general equilibrium analysis of energy efficiency is carried out in two stages. Firstly, the authors introduce an efficiency improvement to reflect an increase of the value of energy expressed in efficiency units, meaning that household can consume the original ‘pre efficiency’ bundle of goods (energy and non-energy) but using less physical energy. This stimulates the wider economy through an increase in the aggregate demand, because household would respond to the lower energy price (expressed in efficiency units) by substituting the consumption of energy goods for the consumption of non-energy goods. However, while in studies focused on industrial energy use, such as Allan et al. (2007) and Turner (2009) the economic expansion is driven by an increase in competitiveness, in Lecca et al. (2014) the demand-led growth puts upward pressure on consumption prices, crowding out exports, determining thereby a decrease in competitiveness.

Secondly, to understand how this loss in competitiveness may be avoided, Lecca et al. (2014) hypothesise that the energy efficiency improvement in household energy use is reflected in an overall decrease in the cost of living. They model this by simply by adjusting the consumer price index (*cpi*) so that it is calculated to include the price of energy goods expressed in efficiency units and the price of non energy goods. Thus, when energy efficiency improves, the *cpi* decreases, increasing competitiveness and putting downward pressure on the nominal wage.

In this paper, we build on the general equilibrium analysis of Lecca et al. (2014), but focusing on a regional case study within the UK, using a single region CGE model of the Scottish economy. In order to underline the implications of moving from a national to a regional context, we initially replicate the type of analysis carried out in Lecca et al. (2014) but using a regional CGE model for Scotland[4]. Then, we extend this analysis by relaxing the assumption of a fixed working population imposed in Lecca et al. (2014) to consider the impacts of interregional migration in response to differences in relative unemployment and wage rates. This provides another mechanism by which reduced competitiveness effects observed in the national case may be reduced.

3 The CGE model

To identify the general equilibrium impacts of energy efficiency we use the AMOS ENVI[5] CGE model for Scotland. This model is based on the general AMOS CGE framework with forward-looking agents explained in Lecca et al. (2013) but extended to incorporate a more detailed structure of the energy demand and supply (Lecca et al., 2014).

AMOS ENVI differs from the UK ENVI model used in Lecca et al. (2014) for at least three reasons. First it is calibrated using data for Scotland, which is a much more open economy than UK as a whole. Second, it does not impose the balance of payments constraint, to reflect the fact that regions do not possess a full range of fiscal and monetary leverage, and receive transfer from the central Government (see Lecca et al., 2013, for a detailed discussion of this aspect). Third, it allows for flow migration, to reflect the free circulation of workers within the UK territory.

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[4] The key differences between the national and the regional modelling contexts are explained in section 3

[5] AMOS is the acronym of a micro-macro model of Scotland and it is the name of a CGE modelling framework developed at the Fraser of Allander Institute, of the University of Strathclyde. ENVI indicates a version of this model developed for the analysis of energy/environmental impacts of a range of policies and other disturbances.

3.1 Consumption

Consumption is modelled to reflect the behaviour of a representative household that maximises its discounted intertemporal utility, subject to a lifetime wealth constraint. The solution of the household optimisation problem, gives the optimal time path consumption of the bundle of goods C_t.

To capture information about household energy consumption, C_t is allocated within each period and between energy goods EC and non-energy goods NEC so that:

$$C_t = \left[\delta^E (\gamma EC_t)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\delta^E) NEC_t^{\frac{\varepsilon-1}{\varepsilon}}\right]^{-\frac{\varepsilon-1}{\varepsilon}} \tag{2}$$

In (2) ε is the elasticity of substitution in consumption, and measures the case with which consumers can substitute energy goods for non-energy goods, $\delta \in (0,1)$ is the share parameter, and γ is the efficiency parameter of energy consumption. The consumption of energy is then divided into two composite goods, coal and refined oil and, electricity and gas, which in turn split into the four energy use, refined oil, coal, electricity and gas, through a nested CES function structure[6]. Moreover, we assume that the individual can consume goods produced both domestically and imported, where imports are combined to domestic goods under the Armington assumption of imperfect substitution (Armington, 1969).

3.2 Production and investment

The production structure reflects the classical KLEM nested CES production function, where capital and labour are combined together to form value added, and energy and materials are combined into intermediate inputs. The combination of intermediate inputs and value added forms gross output. Domestic and imported goods are combined under the Armington assumption (Armington, 1969)[7].

The demand functions for capital and labour are obtained from the first order con-

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[6] See Appendix A.1 for a schematic representation of the consumption structure

[7] See Appendix A.2 for a schematic representation of the production structure.

ditions of the CES production function. Following Hayashi (1982), the optimal time path of investment is derived by maximising the value of firms V_t, subject to a capital accumulation function $\dot{K}_t$, so that:

$$\begin{gathered} \text{Max} V_t \sum_{t=0}^{\infty} \left(\tfrac{1}{1+r}\right)^t \left[\pi_t - I_t \left(1 + g(x_t)\right)\right] \\ \text{subject to } \dot{K}_t = I_t - \delta K_t \end{gathered} \tag{3}$$

where π_t is the firm's profit, I_t is private investment, $g(x_t)$ is the adjustment cost function, with $x_t = I_t/K_t$ and δ is depreciation rate. The solution of the problem gives the law of motion of the shadow price of capital, λ_t, and the adjusted Tobin's q time path of investment (Hayashi, 1982).

3.3 The labour market, wage bargaining and migration

In this specification of the model, wages are determined within the region in an imperfect competition setting, according to the following wage curve:

$$ln\left[\frac{w_t}{cpi_t}\right] = \varphi - \epsilon ln(u_t) \tag{4}$$

where the bargaining power of workers and hence the real consumption wage is negatively related to the rate of unemployment (Blanchflower and Oswald, 2009). In (4), $\dfrac{w_t}{cpi_t}$ is the real consumption wage, φ is a parameter calibrated to the steady state, ϵ is the elasticity of wage related to the level of unemployment u.

In the simulations below, the working population is initially assumed fixed, as in Lecca et al. (2014). However, as we have already argued, regions are much more open systems, and a fixed working population is likely to be inappropriate in a regional context. For this reason, we introduce the following migration function (Lecca et al., 2013):

$$nim_t = \zeta - v^u \left[ln(u_t) - ln(\bar{u}^N)\right] + v^w \left[ln(w_t/cpi_t) - ln(\bar{w}_t^N/\overline{cpi}_t^N)\right] \tag{5}$$

where nim_t is the instantaneous rate of net migration, ζ is a parameter calibrated to ensure zero migration in the first period, and v^u and v^w are elasticities that measures the response to the differences in logs between regional and national unemployment and real wages. In Equation (4) net migration flow is positively related to the difference between the log of regional and national real wages and negatively related to the difference between the log of regional and national unemployment rates (Layard et al., 1991; Treyz et al., 1993). This means for example that when the regional real wage is higher than the national real wage and/or the regional unemployment is lower there will be a net in-migration of workers to the region.

3.4 Modelling energy efficiency and the rebound effect

We define an increase in energy efficiency as any technological improvement that increases the energy services generated by each unit of physical energy (Lecca et al., 2014). This implies that the value of energy in efficiency units has risen. Consequently, the household can achieve the same level of utility by consuming the same amount of non-energy goods and services, but less physical energy.

For simplicity, we follow Koesler et al. (2016) and assume that the energy efficiency is given as a public good, with no cost of implementation for the household. This will ensure comparability with the work of Lecca et al. (2014) for the national case[8].

Following Lecca et al. (2014) we derive the economy-wide rebound effect in two stages. First, we consider the economy-wide rebound in the household sector (R_C) as:

$$R_C = \left[1 + \frac{\dot{E}_C}{\gamma}\right] \cdot 100 \tag{6}$$

where $\dot{E}_C$ measures the proportionate change in household energy consumption, and it can be positive or negative, and γ measures the proportionate change in energy efficiency. Because we are analysing the household economy-wide rebound effect in a full general equilibrium system, $\dot{E}_C$ is a result of a full range of economy-wide adjustments, not just

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[8] This assumption constitutes the focus of our future work

the direct response to the change in the price of the energy service as efficiency increases.

Secondly, to identify the impact of the energy efficiency improvement in the whole economy (i.e. across all industries, household and domestic institutions) we derive the total rebound R_T as follows:

$$R_T = \left[1 + \frac{\dot{E}_T}{\alpha\gamma} \right] \cdot 100 \tag{7}$$

In this case, $\dot{E}_T$ measures the proportionate change in the energy used in the whole economy, and α is the share of household initial energy use in the base year.

It is important to notice that the term $\frac{\dot{E}_T}{\alpha\gamma}$ can be expressed as:

$$\frac{\dot{E}_t}{\alpha\gamma} = \frac{\Delta E_T}{\gamma E_C} = \frac{\Delta E_C + \Delta E_C}{\gamma E_C} = \frac{\dot{E}_C}{\gamma} + \frac{\Delta E_P}{\gamma E_C} \tag{8}$$

where Δ represents absolute change and the subscript P indicates production. Substituting equation (6) and (8) into equation (7) gives:

$$R_T = R_C + \frac{\Delta E_P}{\gamma E_C} \cdot 100 \tag{9}$$

This shows that the total economy-wide rebound will be higher than the household economy-wide rebound if the energy consumption in production increases as result of the improvement in energy efficiency in the household sector.

To obtain additional insights from the nature of rebound, we decompose the total economy-wide rebound into the four energy uses included in the model as follows:

$$R_{Tj} = \left[1 + \frac{\dot{E}_{Tj}}{\alpha_j\gamma} \right] \cdot 100 \tag{10}$$

where the set j includes coal, gas, electricity and refined oil.

3.5 Data and calibration

To calibrate the model we follow a common procedure for dynamic CGE models (Adams and Higgs, 1990), which is to assume that the economy is initially in steady state equilibrium. The structural parameters of the model are derived from the 2009 Social Accounting Matrix (SAM) for Scotland (Emonts-Holley and Ross, 2014), which incorporates the 2009 Input-Output tables for Scotland. The Scottish SAM reports information about economic transactions between industries and other aggregate economic agents, namely the Scottish household, the Scottish Government, and corporate sectors, and accounts for imports and exports to the rest of the UK (RUK) and the rest of the world (ROW). For this paper, we aggregate the SAM to 21 industries[9], including four energy sectors, gas, electricity, coal and refined oil.

The SAM constitutes the core dataset of the AMOS-ENVI model. However other parameters are required to inform the model, such as elasticities, and shares parameters. These are either exogenously imposed, based on econometric estimations or best guesses, or determined endogenously through the calibration process.

To observe the adjustment of all the economic variables throughout time, simulations are repeated simultaneously for 50 periods each equal to one year. We introduce a 5% costless, exogenous and permanent increase in the efficiency of energy used in household consumption. Following this initial 'shock', all the variables start to adjust over time until they reach a new steady state equilibrium. Results are reported for two conceptual periods, the short-run, where labour and capital stocks are fixed, and the long-run, which corresponds to the new steady state equilibrium characterised by no further changes in sectoral capital stocks and population. We also report period by period adjustments given by the discrete solution of the model.

4 Simulation scenarios

Simulations in this paper are divided into four main scenarios, summarised in Table 1. As in Lecca et al. (2014) all the short-run simulations are carried out using two alternative estimates of the elasticity of substitution between consumption of energy and non-energy

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[9] See Appendix B.1 for the full list of sectors included in the model

Table 1: Summary of Simulations

	No Migration	Migration
Standard *cpi*	Scenario 1	Scenario 2
Adjusted *cpi*	Scenario 3	Scenario 4

goods, the short-run elasticity and the long-run elasticity[10]. There are two main reasons for our approach. Firstly, there might be some degree of inertia in the adjustment of household consumption, that would be reflected in a lower response to an energy price change over the short period. Secondly, the energy efficiency improvement may come through an investment in durable goods. In this case, in order to access the efficiency improvement an adjustment of household capital stock would be necessary, and this is generally a long-run adjustment[11]. Apart from this, differences among the four Scenarios are reflected in the way the *cpi* is calculated and by the degree of openess of the labour market as follows.

Scenario 1 . In Scenario 1 we use the AMOS-ENVI model as used in Lecca et al. (2014) but calibrated on a Scottish dataset. The *cpi* is calculated in the standard way and the working population is assumed fixed.

Scenario 2. In Scenario 2 we repeat the same simulations of Scenario 1, using the AMOS-ENVI model with standard *cpi* but expanding the analysis in Lecca et al. (2014) in a regional setting by introducing the migration function described in equation (5).

Scenario 3. In this Scenario we refer to the standard model as in Scenario 1, but assuming the energy efficiency improvement in the household sector is directly reflected in the wage determination process (equation 4), because the *cpi* effectively falls as consequence of the improvement in energy efficiency (Lecca et al., 2014). This is done by adjusting the *cpi* to include the price of energy measured in efficiency units as follows:

$$p_E^F = \frac{p_E}{1+\gamma} < p_E \text{ for } \gamma > 0 \tag{11}$$

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[10] These are based on the recent estimation carried out by Lecca et al. (2014) and are respectively 0.35 and 0.61

[11] We plan to expand this aspect in the future work to analyse the case where the energy efficiency improvement is embedded in an investment in durable goods.

so that

$$cpi_{\tau} = cpi(p_{NE}, p_E^F) \tag{12}$$

In (11) and (12) $p_N E$ is the price of non-energy goods, p_E is the price of energy goods measured in natural units and p_E^F is the price of energy goods measured in efficiency units. When the price of energy in natural units is constant, an increase in efficiency decreases the price of energy in efficiency units, reducing therefore the *cpi* which directly affects the real wage as determined in equation (4). As in Scenario 1, the working population is fixed.

Scenario 4. In Scenario 4 we focus again on the regional setting by repeating the simulations carried out in Scenario 3, with the adjusted *cpi* (as in equations 11 and 12), but now allowing for endogenous migration (equation 5).

To summarise, Scenarios 1 and 3 differ from one another in the way the *cpi* is calculated but they make the same fixed working population assumption. Scenarios 2 and 4 repeat the same simulations as 1 and 3 but assuming full flow migration.

5 Results

5.1 Scenario 1: the standard model with no migration

Table 2 summarises short-run and long-run results of simulations for Scenario 1. In the Table, SR and LR indicate respectively short-run and long-run and ε is the elasticity of substitution in consumption between energy and non-energy goods. In the first column we report short-run results using the short-run elasticity of substitution (0.35). Following the energy efficiency improvement, household energy consumption decreases by 2.67%, while household consumption increases by 0.33%. The higher consumption puts upward pressure on the *cpi*, making domestic products more expensive and reducing thereby international competitiveness. On the other hand, this shift in demand stimulates investment in non energy sector, so that total investment increase by 0.14% and the output of non energy producers rises by 0.07%. This impacts the labour market, where total

Table 2: **% change in the key economic variables in Scenario 1**

Elasticity of substitution	ε SR	ε LR	ε LR
Time period	Short-run		Long-run
GDP	0.04	0.03	0.11
Consumer Price Index	0.09	0.09	0.04
Unemployment Rate	-0.25	-0.21	-0.45
Total Employment	0.06	0.05	0.11
Nominal Gross Wage	0.12	0.11	0.09
Real Gross Wage	0.03	0.02	0.05
Households' Consumption	0.33	0.32	0.40
Investments	0.14	0.16	0.11
Exports	-0.13	-0.12	-0.06
Non-Energy Output	0.07	0.06	0.14
Energy Output	-0.41	-0.23	-0.46
Energy Use	-0.88	-0.47	-0.61
Energy Demand in Production	-0.22	-0.11	-0.30
Households' Consumption of Energy	-2.67	-1.43	-1.48
Household Rebound	46.57	71.45	70.33
Economy-wide Rebound	28.40	61.92	50.08

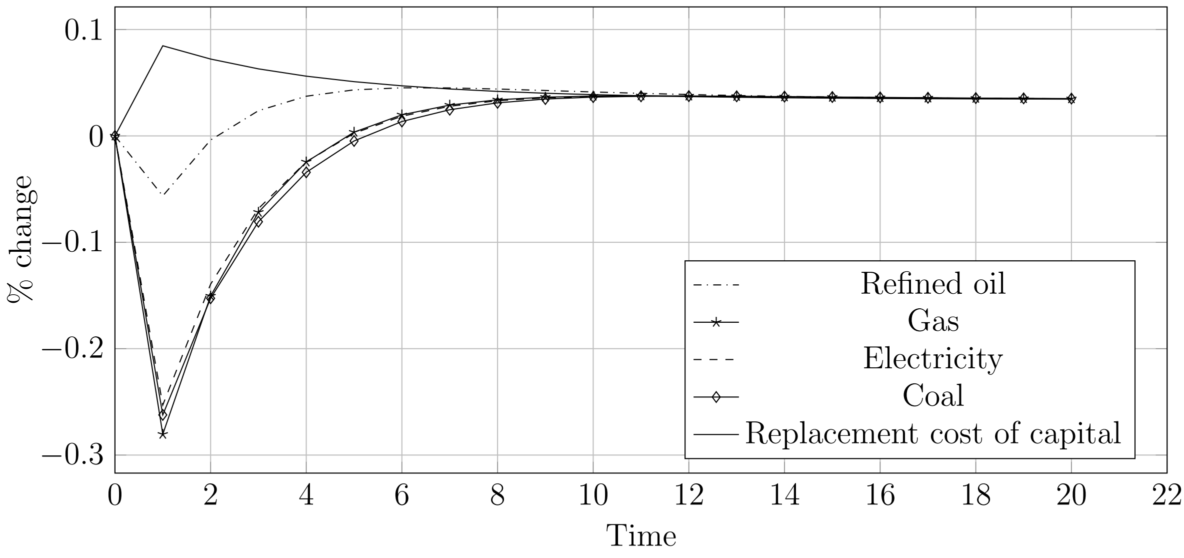
employment increases by 0.06%, unemployment decreases by 0.25% and the real wage is 0.03% higher.

In the second column of Table 2 we report short-run results using the long-run elasticity (0.61). When the elasticity of substitution is low, consumers are more willing to substitute energy goods for non-energy goods. As the elasticity of substitution increases, the degree of substitutability decreases and consumer susbtitute less. In this case, there is less substitution away from energy to non-energy commodities, because the long-run elasticity is higher then the short-run, and this is reflected in a lower decrease in household energy consumption, -1.43%. Given the lower switch in consumption, the economic stimulus is also lower, reflecting the fact that, in the Scottish case, the expenditure in non-energy goods has a higher impact on the economy than the same spending on energy goods.

Long-run results are reported in the third column of Table 2. Scottish GDP increases by 0.11% relative to what it would have been without the efficiency improvement. The fall in household energy demand impacts energy demanded in production, which decreases by 0.22%. This is mostly due to the decreased activity in energy intensive energy suppliers.

In fact, energy production and supply require lots of energy: when household demand less energy, less energy is supplied, and energy producers/suppliers reduce their energy use. For these reasons, the output of energy sectors decreases by 0.41%. Moreover, the initial decrease in demand for energy (as efficiency increases) causes a reduction in the return on capital in energy supply so that, over time, energy suppliers reduce their capacity. This is what Turner (2009) calls 'the disinvestment' effect.

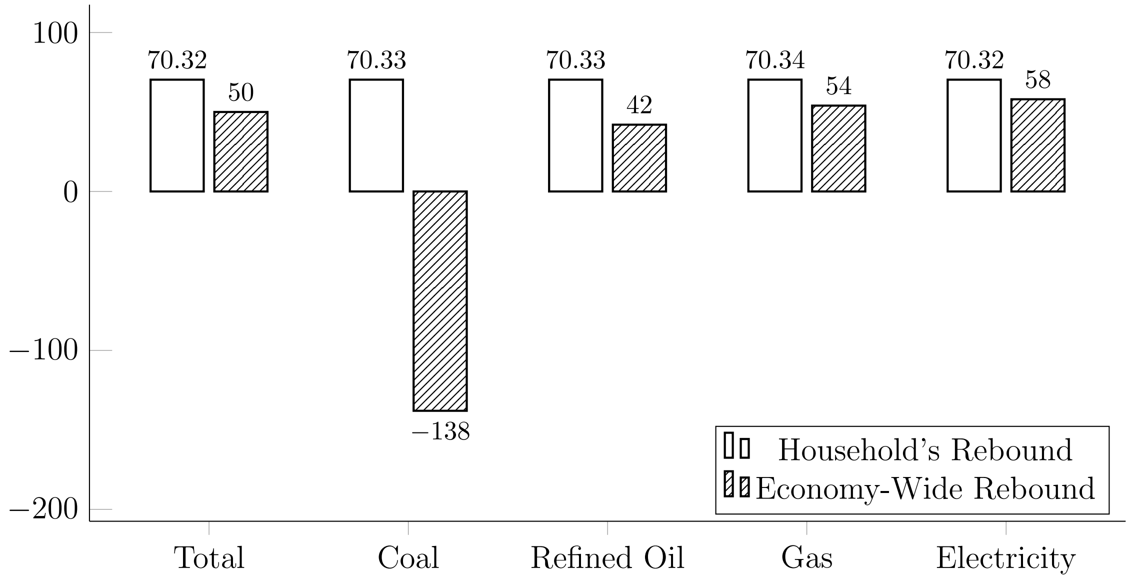
Figure 1: Transitions of shadow price of capital in energy sectors and replacement cost of capital



This can be clearly seen in Figure 1 where we plot the shadow price of capital for the energy sectors and the replacement cost of capital. In the short-run the shadow price of capital of each sectors drops below the replacement cost of capital, so that Tobin's q is lower than 1 and therefore the cost of replacing the capital is higher than the value of the stock, and it is not profitable to invest. Over time, the price of energy rises again, allowing the shadow price of capital to restore and converge asymptotically to the replacement cost of capital, so that Tobin's q again approaches unity. Because of the net contraction in industrial energy use, the overall long-run economy-wide rebound effect (50.08%), is smaller than the general equilibrium household rebound effect (70.33%).

Interesting insights can be obtained by disaggregating the rebound effects for each energy sector using Equation (10). In Figure 2 we plot household and economy-wide rebound effects disaggregated into coal, refined oil electricity and gas. There is significant

Figure 2: Long-run Households and Economy-Wide Rebound Effects in Scenario 1



variation in the economy-wide rebound in the use of different types of energy, reflecting the different composition in the energy used in the production side of the economy. The rebound in the use of electricity and gas is higher than the total economy-wide rebound, while refined oil rebound it is lower. There is a negative rebound in the use of coal, implying that the energy saved in this sector is higher than the expected savings. It is important to notice that household and firms do not usually consume coal directly, but rather they consume electricity produced by coal-fired power stations. When the demand for electricity drops, power stations cut the demand for coal, and this will dramatically reduce the use of such fuel, explaining the negative rebound.

Results from Scenario 1 appear to be in line with findings in Lecca et al. (2014). However, given the higher degree of openess of the goods market of regions, exports decrease in Scotland is higher than what has been found for the national case[12].

5.2 Scenario 2: the standard model with migration

In this Scenario we repeat the simulations of Scenario 1, but including the migration function described by equation (5). Results for key variables are reported in Table 3. To

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[12] In the UK case, exports decrease by 0.8 in the short run and 0.4 in the-run (Lecca et al., 2013).

facilitate the comparison with the no migration case, we add a fourth column reminding us of the long-run results from Scenario 1. Short-run results are quite close to the previous case, because there is no migration in the first period, therefore a comparison is not necessary [13]

Table 3: % change in the key economic variables in Scenario 2

Elasticity of substitution	ε SR	ε LR	ε LR	
Time period	Short-run		Long-run	*LR Scen. 1*
GDP	0.04	0.03	0.17	*0.11*
Consumer Price Index	0.08	0.08	0.00	*0.04*
Unemployment Rate	-0.24	-0.20	0.00	*-0.45*
Total Employment	0.06	0.05	0.18	*0.11*
Nominal Gross Wage	0.11	0.10	0.00	*0.09*
Real Gross Wage	0.03	0.02	0.00	*0.05*
Households' Consumption	0.30	0.30	0.42	*0.40*
Investments	0.15	0.16	0.17	*0.11*
Export	-0.12	-0.11	0.00	*-0.06*
Non-Energy Output	0.07	0.06	0.19	*0.14*
Energy Output	-0.41	-0.23	-0.41	*-0.46*
Energy Use	-0.89	-0.48	-0.57	*-0.61*
Energy Demand in Production	-0.22	-0.12	-0.24	*-0.30*
Households' Consumption of Energy	-2.70	-1.45	-1.47	*-1.48*
Household Rebound	46.03	70.94	70.51	*70.33*
Economy-wide Rebound	27.65	61.22	53.48	*50.08*

In the long-run there is a higher increase in GDP (0.17%), reflecting the higher level of capital stock (0.17%) and employment (0.18%). The differences are driven by the effect of the net in-migration triggered by the initial drop in the unemployment rate and by the rise in the real wage. Following the energy efficiency improvement, workers start to migrate into the region in response to wage and unemployment differentials from the second period. This puts downward pressure on wages, and increases the unemployment rate according to wage setting curve (equation 4). The dynamics of these variables can be seen in Figure 3 where we plot the time path of the real wage, unemployment, *cpi* and exports.

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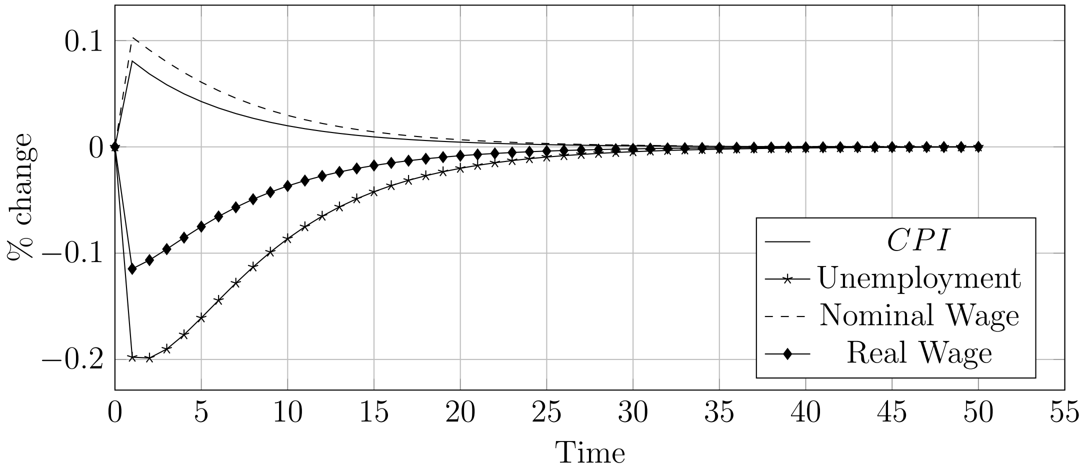
[13] Short-run results are not exactly the same of Scenario 1 as in in this model we have forward-looking agents, therefore some of the effects of migration are anticipated.

Figure 3: Transition Path of Key Variables



The real wage falls and the unemployment rate increases until they both approach zero, when the labour market reaches its long-run equilibrium. Similarly, the *cpi* returns to its base year value, allowing exports to increase again until the original competitiveness is completely restored. This is a crucial result, because it shows that unlike in Scenario 1 and in Lecca et al. (2014), where the higher *cpi* crowds out exports, in a regional economy with free movement of workers, this negative effect on international competitiveness of the increased household energy efficiency disappear in the long-run, due to the effect of migration on prices.

The restored long-run competitiveness contributes to give additional momentum to the economic stimulus. This is reflected in a rise in output of non energy sectors of 0.19%. But because these activities use energy input in production, the energy output drop is slightly less than in previous scenario, likewise the decrease in total energy use. On the other hand, household energy consumption decreases by 1.47%, which is quite close to what happened in Scenario 1. This is because the lower real wage decrease household's labour income, partly mitigating the response in consumption. For this reasons, only the calculated economy-wide rebound effect is higher, (53.5%), while the household rebound is hardly affected.

It is interesting to notice that, the zero variation in prices over the long-run indicates a pure demand response to the introduction of the energy efficiency improvement, similar to what we would expect in an Input-Output modelling framework. This suggests that the nature of the economic expansion observed in this Scenario is demand-driven.

5.3 Scenario 3: the model with adjusted cpi and no migration

In Scenarios 1 and 2, the energy efficiency improvement is modelled so as to reflect a simple change in consumer's taste, with the macroeconomic effects being driven by the change in consumption patterns.

Here we consider the case where the increase in household energy efficiency use is reflected in an overall reduction in the cost of living, by adjusting the *cpi* to include the price of energy calculated in efficiency units according to equations (11) and (12).

Table 4: % change in the key economic variables in Scenario 3

Elasticity of substitution	ε SR	ε LR	ε LR
Time period	Short-run		Long-run
GDP	0.12	0.12	0.33
Consumer Price Index	-0.25	-0.26	-0.38
Unemployment Rate	-0.80	-0.76	-1.38
Total Employment	0.20	0.19	0.34
Nominal Gross Wage	-0.16	-0.17	-0.22
Real Gross Wage	0.09	0.09	0.16
Households' Consumption	0.30	0.30	0.47
Investments	0.44	0.46	0.32
Export	-0.05	-0.05	0.16
Non-Energy Output	0.15	0.14	0.34
Energy Output	-0.38	-0.20	-0.28
Energy Use	-0.85	-0.44	-0.46
Energy Demand in Production	-0.17	-0.07	-0.10
Households' Consumption of Energy	-2.71	-1.48	-1.45
Household Rebound	45.74	70.39	71.07
Economy-wide Rebound	31.00	63.76	63.00

Key results for this case are summarised in Table 4. Unlike Scenario 1, where the *cpi* increases from the first period and remains above the initial level for all 50 periods, and Scenario 2 where it returns to its base year value in the long-run, here the *cpi* decreases both in the short-run and in the long-run, given the lower price of energy in efficiency units. Consequently the nominal wage decreases by 0.16% in the short-run and by 0.22% in the long-run, but because of the lower *cpi* the real wage increases by 0.9% and 0.16%.

The lower price of goods produced domestically stimulates the demand for Scottish goods from the rest of UK and the rest of the World, and although in the short-run exports fall by 0.5% (which is less than what we observed in Scenarios 1 and 2), in the long-run it increases by 0.16%. This difference is crucial in terms of comparison with the standard case, because it says that when the energy efficiency improvement is reflected in less pressure for higher wages, we have a long-run increase in competitiveness, similarly to Allan et al. (2007) and Turner (2009) which focus on industrial energy efficiency. It is also important to notice that given the higher openess of the goods market of regions, the long-run increase in export is significantly higher than what Lecca et al. (2014) find.

The increase in competitiveness along with the switch in the aggregate demand triggers a bigger economic stimulus that is reflected in most of the key macroeconomic indicators. For example, investment increases by 0.44% in the short-run and 0.32% in the long-run. Consequently, the increase in labour and capital used in production has positive effect in output which increases by 0.12% in the short-run and by 0.33% in the long-run [14].

There is a higher demand for energy by industry sectors. Intuitively, when the production of goods and services increases, industry would consume more energy in the production process. However, in the household sector the decrease in energy consumption is in line with what was reported for Scenarios 1 and 2. For this reason, the household rebound is only around 0.5% higher than the standard no migration case. However, the economy wide rebound is higher in Scenario 3, both in the short-run (31%) and in the long-run (63%), reflecting the higher use of energy for industrial purposes. This suggests that the bigger stimulus to economic activity observed in Scenario 3 results in overall a higher use of energy and calculated rebound effect.

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[14] In Lecca et al. (2014) GDP increases by 0.1 in the short-run and 0.24 in the long-run.

5.4 Scenario 4 : the case of migration and adjusted cpi

In the final case, we include both the adjusted *cpi*, equations (11) and (12), and the migration function, equation (5). Results from these simulations are reported in Table 5.

Table 5: % change in the key economic variables in Scenario 4

Elasticity of substitution	ε SR	ε LR	ε LR
Time period	Short-run		Long-run
GDP	0.12	0.11	0.53
Consumer Price Index	-0.27	-0.28	-0.49
Unemployment Rate	-0.77	-0.73	0.00
Total Employment	0.19	0.18	0.54
Nominal Gross Wage	-0.18	-0.19	-0.49
Real Gross Wage	0.09	0.08	0.00
Households' Consumption	0.22	0.22	0.53
Investments	0.46	0.47	0.50
Export	-0.03	-0.02	0.35
Non-Energy Output	0.14	0.13	0.51
Energy Output	-0.38	-0.18	-0.07
Energy Use	-0.88	-0.42	-0.26
Energy Demand in Production	-0.18	-0.06	0.10
Households' Consumption of Energy	-2.79	-1.55	-1.27
Household Rebound	44.17	71.62	74.53
Economy-wide Rebound	28.38	65.36	78.59

In this case, we observe the greatest economic expansion, reflected in most of the macroeconomic indicators. GDP rises by 0.53%, driven by a 0.5% increase in capital stock and 0.54% in employment. The latter is determined by the combined effects of migration and adjusted *cpi* on the labour market.

In the short-run, unemployment decreases by 0.77%, and although the nominal wage falls by 0.18%, the real wage increases by 0.09%, thanks to the decrease in the *cpi*. This triggers interregional net in-migration. Similarly to Scenario 2, the real wage and the unemployment rate start to adjust until they converge to zero in the long-run. This is different from the adjusted *cpi* case with no migration, where in absence of additional workers from abroad the unemployment rate drops by 1.48% in the long-run. However, in this case the *cpi* does not return to zero in the long-run, but it behaves likewise Scenario

3, decreasing in the long-run by 0.49%.

The lower *cpi* encourages individuals to consume more. Household's consumption increases by 0.22% in the short-run, and by 0.53% in the long-run. Because goods produced in Scotland become cheaper for foreign buyers, there is a exports increase by 0.35% over the long-term, similarly to Scenario 3.

The increased competitiveness, along with the shift in domestic aggregate demand, puts upward pressure on the demand for energy in all the productive sectors. In the long-run, energy output decreases by 0.07%, and the overall use of energy in the economy decreases by 0.26%, thanks to a drop in household energy consumption of 1.27%. However, industries raise their long-run energy demand, and unlike all the other scenarios there is a plus 0.1% in the long-run industrial energy use. This is the most interesting result of this Scenario because it underlines that under certain conditions, workers' migrating and responding to the adjusted *cpi*, an increase in energy efficiency in the household sector may lead to an actual increase in industrial energy consumption.

In Figure 4 we plot long-run investment in gas,refined oil, coal and electricity in the four Scenarios. In the first three cases investments are negative in all the energy sectors due to the disinvestment effect described in Scenario 1 (Turner, 2009). However, in Scenario 4 the contraction in investment is lower in gas, coal and electricity, and investment are positive in the oil sector, which is quite important in the Scottish economy.

Because energy used by industries increases more than household energy use in the long-run, the long-run economy-wide rebound effect is higher (even if marginally) than the household rebound effect, which is what we would expect according to the relation expressed in (9).

In Figure 5 we plot the household's and economy-wide rebound effect disaggregate by energy sectors. The economy-wide rebound in oil and electricity is higher than the household rebound, indicating a raise in the use of these fuels in industry. Unlike Scenario 1, where we observed a negative rebound in the oil sector, (see Figure 2), in this case there is a positive 27.9% economy-wide rebound indicating a raise in the demand of such

Figure 4: Long-run investment in the energy sectors

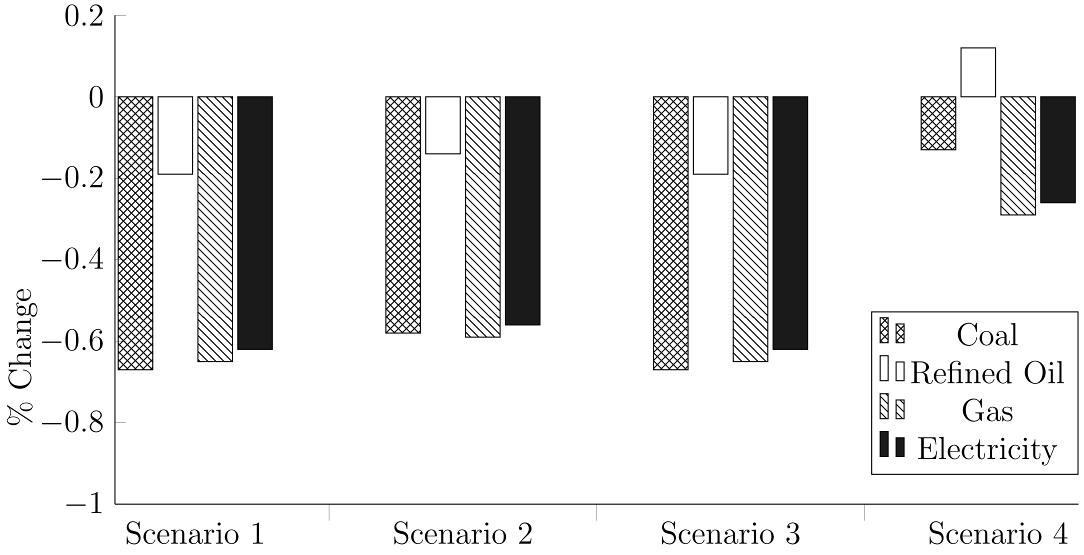
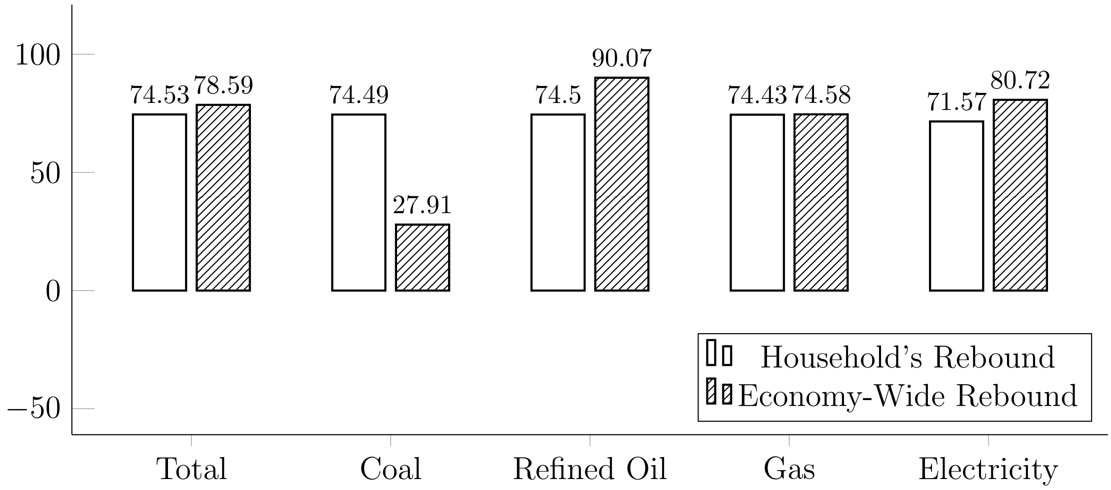


Figure 5: Long-run Household and Economy-Wide Rebound Effects by energy sectors in Scenario 4



fuel.

6 Discussion: trading-off economic benefits and rebound

Results from the four Scenarios show that increasing household energy efficiency in Scotland by 5% would stimulate the Scottish economy. However, there is a clear trade-off between economic benefits and achieved energy savings, which varies across scenarios, depending on whether the efficiency improvement influences the *cpi* and the wage bargaining process, and whether there is migration of workers.

Table 6 summarises the calculated long-run rebound and household rebound effects, and the long-run percentage change in GDP in the four cases. In Scenario 1, with the standard *cpi* and no migration, the economic expansion is triggered by a pure demand shock, which puts upward pressure on domestic prices, crowding out exports. In this case, the calculated household rebound effect is 70.33%, which reduces to 50.08% when the whole economy is considered, so that, overall, 50.08% of the 5% expected energy savings will be offset by increased energy demand. In this Scenario, GDP increases by 0.11%.

Table 6: Long-run economy wide rebound, household rebound, and percentage change in GDP under the four Scenarios

	No migration			Migration		
	R_C	R_T	GDP	R_C	R_T	GDP
Standard *cpi*	70.33	50.08	0.11	70.51	53.48	0.17
Adjusted *cpi*	71.07	63.00	0.33	74.53	78.59	0.53

In Scenario 2, the efficiency change delivers again a pure demand shock, with zero variation of prices in the long-run. The additional working population from the rest of UK allows wages to remain constant in the long-run, further stimulating economic activity. The full adjustment of prices to base year levels, restores the original competitiveness in international markets. This translates as a greater increase in GDP of 0.17%. For this reason, while the household rebound is quite close to the level of Scenario 1, the overall rebound increases to 53.48%, indicating a higher energy demand by industries.

In Scenario 3, where the *cpi* is adjusted to include the price of energy in efficiency units, but there is no migration, we observe an increase in competitiveness in the long-run and the type of stimulus is similar to the productivity-led growth observed in previous work focussed on energy efficiency in production (Allan et al., 2007; Turner, 2009). In this case, the household rebound effect is 71.07%, very close to Scenarios 1 and 2. However, given the stimulus to supply, industries demand more energy, delivering an overall rebound of

63%, and a 0.33% rise in GDP, which is greater than Scenarios 1 and 2.

Lastly, in Scenario 4, the combination of the adjusted *cpi* and migration would cause the largest supply side response, reproducing again the characteristics of a productivity-led stimulus, and triggering the greatest economic expansion. In fact, GDP rises by 0.53% and as we would expect, the economy wide-rebound is 78.6%, which is higher than the household's rebound.

There is a clear trade-off between economic benefits and energy demand reduction, reflected in the fact that the higher is the economic stimulus received from the more efficient use of energy the higher is the rebound effect. However, in none of these scenarios does the calculated rebound effect offset completely the expected energy reduction (i.e no backfire effect), indicating that we can rely to some extent on increasing energy efficiency to reduce energy demand.

7 Conclusions

The simulation results reported in this paper leads us to four fundamental general conclusions for this paper. First, increasing energy efficiency in Scottish households would help to stimulate the economy of the region. However, the type of stimulus is different depending on the precise specification of the shock, and on whether is is a demand shock or a supply shock, in particular when the *cpi* is affected. Second, moving from a national to a regional context, by opening the labour market to migration would result in a general higher economic stimulus, reflecting the restoration of competitiveness in the long-run. Third, when the economic expansion is higher, the difference between potential energy savings and actual energy savings (rebound effects) is also higher, indicating a trade-off between actual energy savings and economic benefits. Fourth, the drivers of the rebound effect are also the drivers of the economic stimulus. Further investigations should explore ways to minimise the magnitude of the rebound effect, without sacrificing the gains in terms of economic welfare.

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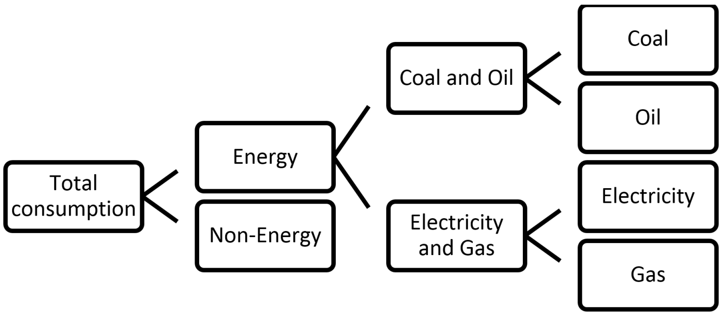
Appendix A

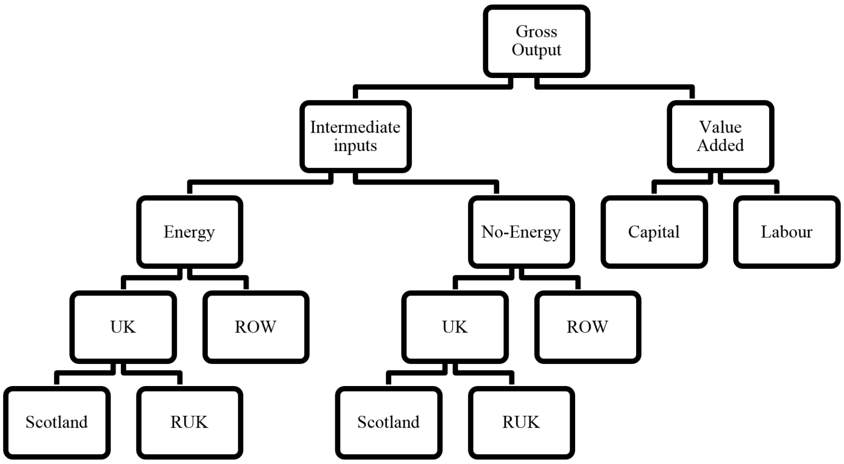
A.1 The structure of Consumption

Figure A.1: The Structure of Consumption



A.2 The structure of production

Figure A.2: The Structure of Production



Appendix B

B.1 Inndustries included in the AMOS ENVI model

Table B.1: The industrial disaggregation of the AMOS ENVI 21- sectors model

Sector's name	**Original sector from the 104 Scot IO table**
Agriculture, forestry and logging	1+2+3
Sea fishing and fish farming	4+5
Mining and extraction	7+8+9
Food, drink and tobacco	10 to 20
Textiles and clothing	21+22+23
Mfr Chemicals etc	28 to 35
Metal and non-metal goods	36+37+38
Transport and other machinery	39+40+41+42+43
Other manufacturing	24+25+26+44+45+46
Water, sewerage and waste	49+50+51
Construction	52+53+54
Distribution	55+56+57+64+65
Transport	58 to 63
Communications, finance and business	66 to 81+83 to 91
R&D	82
Education	93
Public and other services	92+94 to 104
Coal extraction	6
Oil (refining and distribution) and nuclear	27
Gas	47
Electricity	48

Appendix C

C.1 The mathematical presentation of the AMOS-ENVI model

Prices

$$PM_{i,t} = \overline{PM_i} \tag{C.1}$$

$$PE_{i,t} = \overline{PE_i} \tag{C.2}$$

$$PQ_{I,T} = \frac{PR_{i,t} \cdot Ri,t + PM_{i,t} \cdot Mi,t}{Ri,t + Mi,t} \tag{C.3}$$

$$PIR_{I,T} = \frac{\sum_i VR_{i,j,t} \cdot PRj,t + \sum_i VI_{i,j,t} \cdot \overline{PI}_{j,t}}{\sum_i VIRi,j,t} \tag{C.4}$$

$$PY_{j,t} \cdot a_j^Y = \left(PR_{j,t} \cdot (1 - btax_j, sub_j, dep_j) - \sum_i a_{i,j}^y PQj,t \right) \tag{C.5}$$

$$UCK_t = PK_t \cdot (r + \delta) \tag{C.6}$$

$$PC_t^{1-\sigma^C} = \sum_j \delta_j^f \cdot PQ_t^{1-\sigma^C} \tag{C.7}$$

$$PG_t^{1-\sigma^G} = \sum_j \delta_j^g \cdot PQ_t^{1-\sigma^G} \tag{C.8}$$

$$PNE_t = \frac{\sum_z PQ_{z,t} \cdot \bar{V}_z}{\sum_z PQ_z \cdot \bar{V}_z} \tag{C.9}$$

$$PE_t = \frac{\sum_E PQ_{E,t} \cdot \bar{V}_E}{\sum_E PQ_E \cdot \bar{V}_E} \tag{C.10}$$

$$w_t^b = \frac{w_t}{1 + \tau_t} \tag{C.11}$$

$$ln\left[\frac{w_t}{cpi_t}\right] = \varphi - \epsilon ln(u_t) \tag{C.12}$$

$$nim_t = \zeta - \upsilon^u\left[ln(u_t) - ln(\bar{u}^N)\right] + \upsilon^w\left[ln(w_t/cpi_t) - ln(\bar{w}_t^N/\overline{cpi}_t^N)\right] \tag{C.13}$$

$$rk_{j,t} = PY_{j,t} \cdot \delta_j^k \cdot A^{Y\varrho_j} \cdot \left(\frac{Y_{j,t}}{Kj,t}\right)^{1-\varrho_j} \tag{C.14}$$

$$Pk_t = \frac{\sum_j PY_{j,t} \cdot \sum_i KM_{i,j}}{\sum_{i,j} KM_{i,j}} \tag{C.15}$$

Production technology

$$X_{i,t} = A_i^X \cdot \left[\delta_i^y \cdot Y_{i,t}^{\rho_i^X} + (1 - \delta_i^V) \cdot V^{\rho_i^X} i,t\right]^{\frac{1}{\rho_i^X}} \tag{C.16}$$

$$Y_{j,t} = \left(A^{x\rho_j^X}\delta_i^y \cdot \frac{PQ_{j,t}}{PY_{j,t}}\right)^{\frac{1}{1-\rho_j^x}} \cdot X_{i,t} \tag{C.17}$$

$$V_{j,t} = \left(A^{x\rho_j^X}(1 - \delta_i^y) \cdot \frac{PQ_{j,t}}{PV_{j,t}}\right)^{\frac{1}{1-\rho_j^x}} \cdot X_{i,t} \tag{C.18}$$

$$v_{i,t} = A_i^v \cdot \left[\delta_i^v \cdot E_{i,t}^{\rho_i^V} + (1 - \delta_i^V) \cdot NE^{\rho_i^V} i,t\right]^{\frac{1}{\rho_i^V}} \tag{C.19}$$

$$\frac{E_{j,t}}{E_{j,t}} = \left[\left(\frac{\delta_j^v}{1 - \delta_j^v}\right) \cdot \left(\frac{PNE_{j,t}}{PE_{j,t}}\right)\right]^{\frac{1}{1-\rho_j^v}} \tag{C.20}$$

$$VV_{ze,j,t} = \left(A^{z\rho_j^z}(1 - \delta^E N_i) \cdot \frac{PNE_t}{PQ_{E,t}}\right)^{\frac{1}{1-\rho_j^E}} \cdot E_{i,t} \tag{C.21}$$

$$Y_{i,t} = A_i^Y \cdot \left[\delta_i^k \cdot K_{i,t}^{\rho_i^Y} + \delta_i^l \cdot L^{\rho_i^Y} i,t\right]^{\frac{1}{\rho_i^Y}} \tag{C.22}$$

$$L_{j,t} = \left(A^{x\rho_j^Y} \delta_i^l \cdot \frac{PY_{j,t}}{w_t} \right)^{\frac{1}{1-\rho_j^Y}} \cdot Y_{j,t} \tag{C.23}$$

Trade

$$VV_{i,j,t} = Y_i^{vv} \cdot \left[\delta_i^{vm} \cdot VM_{i,t}^{\rho_i^A} + (1 - \delta_i^{vir}) \cdot VIR^{\rho_i^A} i, t \right]^{\frac{1}{\rho_i^A}} \tag{C.24}$$

$$\frac{VM_{i,j,t}}{VIR_{i,j,t}} = \left[\left(\frac{\delta_j^{vm}}{1 - \delta_j^{vir}} \right) \cdot \left(\frac{PIR_{i,t}}{PM_{i,t}} \right) \right]^{\frac{1}{1-\rho_j^A}} \tag{C.25}$$

$$VIR_{i,j,t} = Y_i^{vir} \cdot \left[\delta_i^{vi} \cdot VI_{i,t}^{\rho_i^A} + (1 - \delta_i^{vr}) \cdot VM^{\rho_i^A} i, t \right]^{\frac{1}{\rho_i^A}} \tag{C.26}$$

$$\frac{VR_{i,j,t}}{VI_{i,j,t}} = \left[\left(\frac{\delta_j^{vr}}{1 - \delta_j^{vi}} \right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}} \right) \right]^{\frac{1}{1-\rho_j^A}} \tag{C.27}$$

$$E_{i,t} = \bar{E}_t \cdot \left(\frac{PE_{i,t}}{PQ_{i,t}} \right)^{\rho_i^x} \tag{C.28}$$

Regional demand

$$R_{i,t} = \sum_i VR_{i,j,t} + \sum_i QHR_{i,h,t} + QVR_{i,t} + QGR_{i,t} \tag{C.29}$$

Total absorption equation

$$X_{i,t} + M_{i,t} = \sum_i VV_{i,j,t} + \sum_i QH_{i,h,t} + QV_{i,t} + QG_{i,t} + E_{i,t} \tag{C.30}$$

Households and other domestic institutions

$$U^t(c_t) = \sum_{i=1}^{T-t} (1+\rho)^{-t} \frac{C_t^{1-\sigma} - 1}{1 - \sigma} \tag{C.31}$$

$$\frac{C_t}{C_{t+1}} = \left[\frac{PC_t \cdot (1+\rho)}{PC_{t+1} \cdot (1+r)} \right]^{-\frac{1}{\sigma}} \tag{C.32}$$

$$W_t = NFW_t + FW_t \tag{C.33}$$

$$NFW_t(1+r) = NFW_{t+1} + (1-\tau_t)L^s_t(1-u_t)w_t + Trf_t \tag{C.34}$$

$$FW_t(1+r) = FW_{t+1} + \Pi_t + S_t \tag{C.35}$$

$$Trf_t = Pc_t \cdot \overline{Trf} \tag{C.36}$$

$$S_t = mps \cdot \left[(1-\tau_t)\, L^s_t(1-u_t)w_t + Trf_t\right] \tag{C.37}$$

$$\Pi = d^h \cdot \sum_i rk_{i,t}K_{i,t} \tag{C.38}$$

$$C_t = \left[\delta^E(\gamma EC_t)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\delta^E)NEC_t^{\frac{\varepsilon-1}{\varepsilon}}\right]^{-\frac{\varepsilon-1}{\varepsilon}} \tag{C.39}$$

$$Ec_t = \left(\gamma^{\rho e}\delta^E \cdot \frac{Pc_t}{PE_t}\right)^{\frac{1}{1-\rho e}} \cdot C_t \tag{C.40}$$

$$Ec_t = \left[\delta^{co}CO_t^{\rho_g} + (1-\delta^{co})EG_t^{\rho_g}\right]^{\frac{1}{\rho_g}} \tag{C.41}$$

$$\frac{CO_t}{EGc_t} = \left[\left(\frac{\delta^c o}{1-\delta^c o}\right) \cdot \left(\frac{PEG_t}{PCO_t}\right)\right]^{\frac{1}{1-\rho^g}} \tag{C.42}$$

$$CO_t = \left[\delta^{cl}CL_t^{\rho_o} + (1-\delta^{co})OIL_t^{\rho_o}\right]^{\frac{1}{\rho_o}} \tag{C.43}$$

$$\frac{CL_t}{OIL_t} = \left[\left(\frac{\delta^{cl}}{1-\delta^{cl}}\right) \cdot \left(\frac{PQ_{oil,t}}{PQ_{coal,t}}\right)\right]^{\frac{1}{1-\rho^0}} \tag{C.44}$$

$$QH_{z,t} = \left(\delta^{f \rho_i^c} \cdot \frac{Pc_t}{PQ_{z,t}} \right)^{rho_i^c} \cdot NEc_t \tag{C.45}$$

$$EG_t = \left[\delta^{Ele} Ele_t^{\rho_{el}} + (1 - \delta^{el}) GAS_t^{\rho_{el}} \right]^{\frac{1}{\rho_{el}}} \tag{C.46}$$

$$\frac{Ele_t}{GAS_t} = \left[\left(\frac{\delta^{GAS}}{1 - \delta^{GAS}} \right) \cdot \left(\frac{PQ_{GAS,t}}{PQ_{Ele,t}} \right) \right]^{\frac{1}{1-\rho^{el}}} \tag{C.47}$$

$$QH_{ele,t} = Ec_t \tag{C.48}$$

$$QH_{GAS,t} = GAS_t \tag{C.49}$$

$$QH_{Coal,t} = CL_t \tag{C.50}$$

$$QH_{OIL,t} = OIL_t \tag{C.51}$$

$$QH_{I,t} = \gamma_i^f \left[\delta^{hir} QHIR_t^{\rho_i^A} + (1 - \delta^{hm}) QHM_t^{\rho_i^A} \right]^{\frac{1}{\rho_i^A}} \tag{C.52}$$

$$\frac{QHIR_{i,t}}{QHM_{i,t}} = \left[\left(\frac{\delta_i^{hir}}{1 - \delta_i^{hm}} \right) \cdot \left(\frac{PM_{i,t}}{PR_{i,t}} \right) \right]^{\frac{1}{1-\rho^A}} \tag{C.53}$$

$$QHIR_{I,t} = \gamma_i^{fir} \left[\delta^{hr} QHR_t^{\rho_i^{hr}} + \delta^{hi} QHI_t^{\rho_i^A} \right]^{\frac{1}{\rho_i^A}} \tag{C.54}$$

$$\frac{QHR_{i,t}}{QHI_{i,t}} = \left[\left(\frac{\delta_i^{hr}}{1 - \delta_i^{hi}} \right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}} \right) \right]^{\frac{1}{1-\rho^A}} \tag{C.55}$$

Government

$$FD_t = G_P g_t + \sum_{dgins} TRGdngins, t \cdot PC_t - \\ \left(d^g \cdot \sum_i rki, t \cdot K_{i,t} + \sum_i IBTi, t + \sum_i Lj, t \cdot w_t + \overline{FE} \epsilon_t \right) \tag{C.56}$$

$$QG_{i,t} = \delta_i^g \cdot G_t \tag{C.57}$$

$$QGR_i, t = QG_i, t; QGM_i, t = 0; \tag{C.58}$$

Investment demand

$$QV_{i,t} = \sum_j KM_{i,j} \cdot J_{j,t} \tag{C.59}$$

$$QV_{I,t} = \gamma_i^v \left[\delta^{qvm} QVM_t^{\rho_i^A} + (1 - \delta^{qvir}) QVIR_t^{\rho_i^A} \right]^{\frac{1}{\rho_i^A}} \tag{C.60}$$

$$\frac{QVM_{i,t}}{QVIR_{i,t}} = \left[\left(\frac{\delta_i^{qvm}}{\delta_i^{qvir}} \right) \cdot \left(\frac{PIR_{i,t}}{PM_{i,t}} \right) \right]^{\frac{1}{1-\rho^A}} \tag{C.61}$$

$$QVIR_{I,t} = \gamma_i^{vir} \left[\delta^{qvi} QVI_t^{\rho_i^A} + (1 - \delta^{qvr}) QVR_t^{\rho_i^A} \right]^{\frac{1}{\rho_i^A}} \tag{C.62}$$

$$\frac{QVR_{i,t}}{QVI_{i,t}} = \left[\left(\frac{\delta_i^{qvr}}{\delta_i^{qvi}} \right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}} \right) \right]^{\frac{1}{1-\rho^A}} \tag{C.63}$$

Time path of investment

$$J_{i,t} = I_{i,t} \left(1 - bb - tk + \frac{\beta}{2} \frac{\left(\frac{I_{i,t}}{K_{i,t}} - \alpha \right)^2}{\frac{I_{i,t}}{K_{i,t}}} \right) \tag{C.64}$$

$$\frac{I_t}{K_t} = \alpha + \frac{1}{\beta} \cdot \left[\frac{\lambda_{i,t}}{Pk_t} - (1 - bb - tk) \right] \tag{C.65}$$

$$\dot{\lambda}_{i,t} = \lambda_{i,t}(r_t + \delta) - R^k_{i,t} \tag{C.66}$$

$$\theta(x_t) = \frac{\beta}{2}\frac{(x_t - \alpha)^2}{x_t}; \text{and } x_t = \frac{x_t}{k_t} \tag{C.67}$$

$$R^k_{i,t} = rk_t - Pk + t\left[\frac{I_{i,t}}{K_{i,t}}\right]^2 \theta'_t(I/K) \tag{C.68}$$

Factors accumulation

$$KS_{i,t+1} = (1 - \delta)KS_{i,t} + I_{i,t} \tag{C.69}$$

$$K_{i,t} = KS_{i,t} \tag{C.70}$$

$$LS_t \cdot (1 - u_t) = \sum_j L_{j,t} \tag{C.71}$$

Indirect taxes and subsidies

$$IBT_{i,t} = btax_i \cdot X_{i,t} \cdot PQ_{i,t} \tag{C.72}$$

Total demand for import and current account

$$M_{i,t} = \sum_i VI_{i,j,t} + \sum_i VM_{i,j,t} + \sum_i QHM_{i,h,t} + QGM_{i,t} + QVI_{i,t} + QVM_{i,t} \tag{C.73}$$

$$TB_t = \sum_i M_{i,t} \cdot PM_{i,t} - \sum_i E_{i,t} \cdot PE_{i,t} + \epsilon \cdot \left(\sum_{dngins} \overline{REM}_{dngind} + \overline{FE}\right) \tag{C.74}$$

Assets

$$VF_{i,t} = \lambda_{i,t} \cdot K_{i,t} \tag{C.75}$$

$$D_{t+1} = (1 + r) \cdot D_t + TB + t \tag{C.76}$$

$$Pg_{t+1} \cdot GD_{t+1} = \left[1 + r + \left(\frac{Pc_{t+1}}{Pc_t} - 1\right)\right] \cdot PG_t \cdot Gd_t + FD_t \tag{C.77}$$

Steady state conditions

$$\delta \cdot KS_{i,T} = I_{i,t} \tag{C.78}$$

$$R^k_{i,T} = \lambda_{i,T}(r + \delta) \tag{C.79}$$

$$FD_t = \left[1 + r + \left(\frac{Pc_{t+1}}{Pc_t} - 1\right)\right] \cdot PG_t \cdot Gd_t \tag{C.80}$$

$$TB_T = r \cdot D_t \tag{C.81}$$

$$NFW_t \cdot r = (1 - \tau_t)L^s_t(1 - u_t)w_t + Trf_t \tag{C.82}$$

$$FW_t \cdot r = \Pi - S_t + Trf_t \tag{C.83}$$

To produce short-run and long-run results

$$KS_{i,t=1} = KS_{i,t=0} \tag{C.84}$$

$$LS_{i,t=1} = LS_{i,t=0} \tag{C.85}$$

$$GD_{i,t=1} = GD_{i,t=0} \tag{C.86}$$

$$D_{i,t=1} = D_{i,t=0} \tag{C.87}$$

Glossary

i,j (*i*=*j*)	the set of goods or industries
ins	the set of institutions
dins ($\subset ins$)	the set of domestic institutions
dngins ($\subset dins$)	the set of non-government institutions
E ($\subset i$)	the set of energy sectors {*Coal, Ele, Gas and Oil*}
z ($\subset i$)	the set of non-energy sectors

Prices

$PY_{i,t}$	value added price
$PR_{i,t}$	regional price
$PQ_{i,t}$	output price
$PIR_{i,t}$	national commodity price (regional + ROI)
$PI_{i,t}$	price of RUK commodities
$rk_{i,t}$	rate of return to capital
w_t	unified nominal wage
w_t^b	after tax wage
Pk_t	capital good price
UCK_t	user cost of capital
$\lambda_{i,t}$	shadow price of capital
Pc_t	aggregate consumption price
Pg_t	aggregate price of Government consumption goods
ε	exchange rate [fixed]

Endogenous variables

$X_{i,t}$	total output
$R_{i,t}$	regional supply
$M_{i,t}$	total import
$E_{i,t}$	total export (interregional + international)
$Y_{i,t}$	value added
$L_{i,t}$	labour demand
$K_{i,t}$	physical capital demand
$KS_{i,t}$	capital stock
$LS_{i,t}$	labour supply

$VV_{i,j,t}$	total intermediate inputs in *i* and *j*
$V_{i,t}$	Total intermediate inputs in *i*
$VR_{i,j,t}$	regional intermediate inputs
$VM_{i,j,t}$	ROW intermediate inputs
$VIR_{i,j,t}$	national intermediate inputs (ROW+RUK)
$VI_{i,j,t}$	ROI intermediate inputs
$G_{i,t}$	aggregate government expenditure
$QG_{i,t}$	total government expenditure by sector *i*
$QGR_{i,t}$	regional government expenditure
$QGM_{i,t}$	government expenditure(ROI+ROW)
C_t	aggregated household consumption
Ec_t	household consumption of energy
NEc_t	household consumption of non-energy goods and services
CO_t	household consumption of Coal and and Oil
EG_t	household consumption of Electricity and Gas
Ele_t	household consumption of Electricity
GAS_t	household consumption of Gas
CL_t	household consumption of Coal
Oil_t	household consumption of Oil
$QH_{i,t}$	total households consumption in sector *i*
$QHR_{i,t}$	regional consumption in sector *i*
$QHIR_{i,t}$	regional+RUK consumption in sector *i*
$QHM_{i,t}$	import consumption in sector *i*
$QV_{i,t}$	total investment by sector of origin *i*
$QVR_{i,t}$	regional investment by sector of origin *i*
$QVM_{i,t}$	ROW investment demand
$QVIR_{i,t}$	national investment (Regional+RUK)
$QVI_{i,t}$	ROI investment demand
$I_{j,t}$	investment by sector of destination *j*
$J_{j,t}$	investment by destination *j* with adjustment cost
u_t	regional unemployment rate
$R^k_{i,t}$	marginal net revenue of capital
S_t	domestic non-government saving
Trf_t	households net transfer

$TRSF_{dngins,dnginsp,t}$	transfer among *dngins*
$HTAX_t$	total household tax
TB_t	current account balance

Exogenous variables

$\overline{REM}_t$	remittance for *dngins*
$\overline{FE}_t$	remittance for the Government
$GSAV_t$	government saving
r	interest rate

Elasticities

σ	constant elasticity of marginal utility
ρ_i^X	elasticity parameter between intermediate inputs and value added
ρ_i^Y	elasticity parameter between capital and labour
ρ_i^A	in Armington function
σ_i^x	of export with respect to term of trade
σ_i^e	Substitution between energy and non-energy in Household consumption
σ_i^g	Substitution elasticity between CO and EG in Household consumption
σ_i^o	Substitution elasticity between Coal and Oil in Household consumption

Parameters

$a_{i,j}^V$	Input-output coefficients for *i* used in *j*
a_j^Y	share of value added on production
$\delta_j^{Y,V}$	shares in CES output function in sector *j*
$\delta_j^{k,l}$	shares in value added function in sector *j*
$\delta_{i,j}^{vir,vm,vr,vi}$	shares parameters in CES function for intermediate goods
$\delta_{i,j}^{qvir,qvm,qvr,qvi}$	shares parameters in CES function for investment goods
$\delta_{i,h}^{E,co,cl}$	shares parameters in CES function for households consumption
$\delta_{i,h}^{hr,hm}$	shares parameters in CES function for households consumption
$\delta_i^{gr,gm}$	shares parameters in CES function for government consumption

$\gamma_{i,j}^{vv,vir}$	shift parameter in CES functions for intermediate goods
γ_i^f	shift parameter in CES function for households consumption goods

γ_i^g	shift parameter in CES function for government consumption
$btax_i$	rate of business tax
$KM_{i,j}$	physical capital matrix
mps	rate of saving in institutions *dngins*
τ	rate of income tax
ρ	pure rate of consumer time preference
bb	rate of distortion or incentive to investment
δ	rate of depreciation
γ	efficiency shock in household consumption