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THE IMPORTANCE OF ENERGY PRICE STICKINESS AND REAL WAGE INFLEXIBILITY FOR THE TIME PATHS OF REBOUND EFFECTS

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The importance of energy price stickiness and real wage inflexibility for the time paths of rebound effects

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Abstract

There has been some controversy over the relative sizes of the short- and long-run rebound effects associated with energy efficiency improvements. Theoretical analysis by Wei (2007) and Saunders implied that the rebound effects would always be greater in the long-run than in the short-run. However, Allan et al (2007) and Turner (2009) found evidence from Computable General Equilibrium simulations that contradicted this result. In this paper we systematically explore the impact of energy price stickiness and real wage inflexibility for the evolution of rebound effects. We find that: the degree of energy price, but not wage, stickiness is an important determinant of the time path of rebound effects and of its relative size in the short- and long-runs; and that there is considerable variation in the scale of rebound effects through time, even where short-run rebound effects are lower than in the long-run. However, the most significant finding overall is that rebound reflects the system-wide interaction between energy producing and energy using sectors.

Key Words: energy efficiency, evolution of energy rebound, price stickiness, real wage inflexibility

JEL codes: C68; D58; Q43; Q48

1. Introduction

There has been some controversy over the relative sizes of the short- and long-run rebound effects associated with energy efficiency improvements. Theoretical analysis by Wei (2007) and Saunders (2008) implied that the rebound effect would always be greater in the long-run than in the short-run. However, Allan et al (2007) and Turner (2009) found evidence from Computable General Equilibrium (CGE) model simulations that contradicted this result. Turner (2009) argued that the limitation of the earlier theoretical analyses lay in their assumption of a constant capital rental rate.

Broadly, the argument in favour of higher rebound in the long run is that the fall in the price of energy, measured in efficiency units, increases the competitiveness of energy-using industries, and simultaneously increases the real wage. These impacts both encourage and allow expansion which is limited in the short run by the fixed capital stock. Long-run capital accumulation relaxes the capacity constraint in these energy-using industries and therefore increases energy demand, measured in efficiency units, and the size of the rebound effect.

However, there are opposite capital adjustments occurring in energy-producing industries which generate offsetting effects on energy demand. In the short run there is excess capacity in these sectors, so that the price of energy, measured in natural units, will fall as the result of falling capital rentals: essentially, there is falling profitability in the energy sectors in the face of reduced energy demand. Energy production is capital intensive so that the short-run fall in prices is large and goes some way to shore up short-run energy production and sales.

But reduced profitability leads to subsequent disinvestment in the energy sectors, with the capital rentals over time returning to their original value. In line with the reduction in capacity, the price of energy, measured in natural units, will move back towards its initial value. In the CGE simulations in Allan et al (2007) and Turner (2009), the increase in energy demand generated by the short-run reduction in energy prices as a result of temporary overcapacity in energy supply sectors is greater than the expansion in energy demand as the short-run capacity constraints in the energy using sectors are relaxed. This leads to a reversal of the expected relative size of the rebound effects over time.

This result depends upon the flexibility of short-run prices in the energy sector which, at least partly, reflects the assumption of perfect competition in these sectors. But post-Keynesian macro-models argue for the adoption of sticky prices in an imperfectly competitive setting. Further, there are particularly high levels of concentration in the UK energy market, especially at the local level. The sector is frequently criticised in the media for price rigidity, particularly in a downwards direction. However, if such rigidity exists, this would undermine the rationale for a high short-run rebound.

This paper extends Turner's (2009) analysis in three main respects. First, and most importantly, we consider the extent to which the time path of rebound effects is sensitive to the flexibility of energy prices. As far as we are aware this is the first CGE analysis that explicitly allows for price inflexibilities in the energy supply industry. Second, we also explore the impact of real wage stickiness in a manner that is completely symmetrical to our treatment of price inflexibility. Finally, we study the entire evolution of rebound effects, not simply their short and long run values. This highlights the considerable sensitivity of the measurement of rebound to the precise timing at which that measurement takes place, a potentially important finding for energy policy.

We find that: the degree of price but not wage stickiness is indeed an important determinant of the time path of rebound (and of its relative size in the short- and long-runs) and that there is considerable variation in the scale of rebound effects through time, even where short-run rebound effects are lower than in the long-run. However, the most significant finding overall is that rebound reflects the system-wide interaction between energy producing and energy using sectors.

In Section 2 of the paper we discuss the motivation for moving away from the conventional neoclassical CGE assumptions of perfect price and real wage flexibility. Section 3 sets out definitions of rebound effects. In Section 4 we outline our intertemporal, energy-economy-environment CGE model of the UK economy, with a particular focus on our treatment of price and wage inflexibility. We present the simulation results in Section 5 and brief conclusions in Section 6.

2. Price and wage flexibility

Price stickiness

There is an extensive literature on potential sources of price stickiness that inhibit prices adjusting instantaneously to changes in demand and supply conditions. These typically involve some form of imperfect competition that affords firms an element of price-setting power. Traditionally, these ideas were based on pragmatic considerations and a degree of empirical evidence. So Hall and Hitch (1939) suggested widespread use of a mark-up pricing model, according to which prices were marked up over marginal costs plus some contribution towards fixed costs. Leontief (1951) emphasised input price inflexibility as a key determinant of product price stickiness, so that nominal wage rigidity in labour-intensive industries would be an important source of inflexibility, and we consider this below.

However, in view of the potential macroeconomic significance of price stickiness, there has been considerable activity seeking to establish theoretical micro-foundations for New Keynesian macroeconomics by providing convincing explanations for price (and wage) inflexibilities. Older

Keynesian models were regarded as incomplete, content to take significant wage and price inflexibilities as a stylised fact. The presence of even modest menu costs can give rise to significant price inflexibilities. These are transactions costs associated with changes in prices, analogous to changing the menus in restaurants.

A second consideration is that large firms tend to set prices in a way that would broadly be regarded as fair. Okun's (1981) notion of customer, as opposed to auction, markets provides a further rationale for firms deviating from conventional short-run profit maximising behaviour. If their relationship with customers is important, this, in particular, inhibits rapid price adjustments that risk being regarded as unfair, thereby undermining customer confidence and encouraging a switch to an alternative supplier. Indeed, many prices are subject to agreed contracts that run into the future and are therefore inherently "sticky", although the degree of stickiness may well be sensitive to the importance of the fundamental reasons for price inflexibilities.

Oligopolistic market structures have long-since been regarded as a likely source for price inflexibilities. Fear of rivals' reactions to any individual firm's price changes can act to inhibit the latter, although of course, the oligopolistic motivation for price stickiness is not dependent on the very special assumptions of the kinked demand curve model.

These sources of price inflexibility are not necessarily competing and, in practice, the presence of price stickiness may reflect the impact of a number of influences. In the case of energy prices in the UK a number of these considerations are germane.[1] The market is oligopolistic in structure. There is also widespread concern about the fairness of any price adjustments. This arises initially among consumers, particularly in relation to the possible abuse of market power, which spills over into political sensitivity about substantial price adjustments. These considerations inhibit the kind of instantaneous responses of prices to supply and demand changes that are presumed in conventional models of perfectly competitive markets.

In this paper we augment our energy, economy, environment CGE model, UKENVI, to capture such behaviour. While there is empirical evidence that supports the presence of price inflexibility in general and for the energy price in particular, for example Bunn and Fezzi (2008), we do not estimate such models here. Rather we explore the impact of varying degrees of energy price stickiness for the measurement of rebound effects.

Wage inflexibility

[1] Others seem much less so. For example, the capital intensity of the energy supply industry suggests that wage inflexibility is unlikely, in itself, to be a major explanation of energy price inflexibilities.

Conventional competitive labour market models assume that wages adjust to equate labour demands and supplies in each period, which, at the macroeconomic level, carries the dubious implication that all unemployment is voluntary. However, the presence of unions and wage bargaining and efficiency wage considerations provide a rationale for limits to real wage flexibility relative to the competitive case, and for the persistence of involuntary unemployment.

The wage curve, in which the workers' bargained real wage is directly related to their bargaining power, and therefore inversely to the unemployment rate, has amassed considerable empirical support across a range of countries and time periods (e.g. Blanchflower and Oswald, 1994). While this approach typically rejects a competitive interpretation of labour market behaviour it still allows wage flexibility in the sense that the real wage can rapidly adjust in response to changes in labour market conditions. However, the presence of multi-period nominal (and real) wage contracts imparts a degree of stickiness to nominal and real wage flexibility in practice. Again, attempts to provide rigorous microeconomic foundations for New Keynesian macroeconomics have generated a range of models explaining the presence of wage stickiness in terms of rational economic behaviour. These include contracting models; insider-outsider theories; efficiency wage theories etc.

3. Energy efficiency and the rebound effect

In this paper we identify the impact of a costless and exogenous improvement in the efficiency with which energy is used as an intermediate input in production across all sectors of the economy. We define an increase in energy efficiency as a technological improvement that increases the energy services generated by each unit of physical energy (Allan et al., 2007).[2] This implies that the energy in efficiency units, E_f, supplied by a given amount of energy measured in physical (or natural) units, E_p, has increased. Specifically, if there has been a γ proportionate increase in energy efficiency:

$$E_f = (1+\gamma)E_p \qquad (1)$$

The implication of such an energy efficiency improvement is that firms can achieve the same level of production by using the same amount of non-energy inputs, such as capital, labour and other intermediates, but γ less physical energy.

[2] Just for complete clarity, in this case the efficiency improvement is limited to where energy is used as an intermediate in production.

However, as a result of the efficiency improvement the price of energy used as an intermediate in production, measured in efficiency units, p_f^e falls. Specifically, if the price in natural (physical) units is p_p^e, then:

$$p_f^e = \frac{p_p^e}{1+\gamma} \tag{2}$$

This change in the price of energy has substitution and output effects which typically mean that the reduction in the use of energy is less than would be expected from an engineering point of view. The extent of this shortfall is called the rebound effect. In this case, the rebound in the use of energy as an intermediate in production, R_I, is:

$$R_I = \left[1 + \frac{\dot{E}_I}{\gamma}\right] 100 \tag{3}$$

In equation (3) $\dot{E}_I$ is the proportionate change in physical energy use in production after the efficiency shock If the proportionate reduction in energy use equals the effective increase in total energy productivity, so that $-\dot{E}_I = \gamma$, then R_I is zero and there is no intermediate rebound. However, if the proportionate reduction in energy use in production is less than the increase in efficiency, then rebound occurs.

The efficiency improvement in the use of energy in production impacts energy use through a number of channels. There are two direct channels. The first is the move to more energy-intensive, measured in efficiency units, production techniques. This reflects the corresponding fall in the price of energy and the subsequent substitution towards energy. This means that the proportionate fall in energy use per unit of output, now measured in natural units, is less than the efficiency improvement. The second channel is the increased competitiveness of all production sectors. This is driven by the reduced energy costs associated with the direct efficiency improvement.

Both the substitution and competitiveness effects increase the scale of rebound. A further indirect effect comes through the fall in price of all intermediate inputs which results from the lower effective energy price. This further stimulates competitiveness effects. These increases in sectoral outputs, driven by competitiveness effects, are accompanied by increases in the derived demand for the energy input. A fourth factor, but one that influences rebound in the opposite direction, is the reduction in energy use operating through the energy sector supply chain. Energy production is itself energy intensive. A reduction in demand for energy in all production sectors will further reduce the demand for energy in the production of energy itself. This fourth channel therefore reduces the rebound value.

Equation (3) focusses solely on the use of energy in production. However, there will also be impacts on the use of energy in final demand. These will stem from competitiveness changes that result from endogenous price changes, and also from income changes that occur as economic activity and total household income change. Total, economy-wide, rebound arising from a stimulus to energy efficiency in production is defined as R_T. It implicitly incorporates general equilibrium feedback effects on the total of energy uses, not just use in production. It is defined as:

$$R_T = \left[1 + \frac{\dot{E_T}}{\alpha\gamma}\right] 100, \tag{4}$$

Where: $\dot{E_T}$ is the change in total physical energy use after all agents have adjusted their behaviour to the technical energy efficiency improvement and α is the share of energy use in production in total energy use in the base year. If the percentage reduction in total energy use equals the effective increase in total energy productivity, so that $-\dot{E_T} = \alpha\gamma$, then R_T is zero and there is no economy-wide rebound. Economy-wide rebound occurs if the proportionate reduction in energy use is less than the effective increase in efficiency.

The term $\dot{E_T}/\alpha\gamma$ can be expressed as:

$$\frac{\dot{E_T}}{\alpha\gamma} = \frac{\Delta E_T}{\gamma E_I} = \frac{\Delta E_I + \Delta E_C}{\gamma E_I} = \frac{\dot{E_I}}{\gamma} + \frac{\Delta E_C}{\gamma E_I}, \tag{5}$$

where Δ represents absolute change and E_C is energy use in consumption. Substituting equation (5) into equation (4) and using equation (3) gives:

$$R_T = R_I + \left[\frac{\Delta E_C}{\gamma E_I}\right] 100. \tag{6}$$

Equation (6) implies that the total economy-wide rebound, R_T, will be larger (smaller) than rebound in production, R_I, if there is a net increase (decrease) in energy use in household final consumption.

The changes in domestic energy used in household consumption are driven by changes in product prices and household income. We expect real household income to rise as the result of the increase in energy efficiency, which tends to increase rebound. Changes in price will depend on the general equilibrium adjustments to prices together with the change in technology. To the extent that energy prices fall relative to other commodities, rebound will rise in response to price-sensitivity in household consumption.

The factors that we have discussed up to now in this section reflect the long-run changes that will affect the economy as a result of the energy efficiency shock. But as we argue in the introduction, in the process of adjustment there will be endogenous changes in the degree of over- and under-capacity across individual sectors of the economy which will also affect the endogenous prices and therefore energy use. It is these effects which are central to the present paper.

4. The CGE model

We simulate the economy-wide and sectoral impacts of improving energy efficiency in production using a variant of the UK Computable General Equilibrium model UKENVI. This is a CGE modelling framework designed for the analysis of economic disturbances to the UK economy, where the ENVI version is specifically designed to analyse energy and environmental policies. In the following sections we provide a description of the main characteristics of the model.[3]

4.1 Consumption

In the myopic version of UKENVI that we employ here, to facilitate comparison with previous results reported in the literature, consumption in any period, C_t , is a linear homogeneous function of real disposable income. 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:

$$C_t = \left[\delta^E (EC_t)^{\frac{\varepsilon -1}{\varepsilon}} + (1-\delta^E) TNEC_t^{\frac{\varepsilon -1}{\varepsilon_h}}\right]^{-\frac{\varepsilon}{\varepsilon -1}} \quad (7)$$

In (7) ε is the elasticity of substitution in consumption. It measures the ease with which consumers can substitute energy goods for non-energy goods. The parameter δ ∈ (0,1) is the share parameter. Moreover, we assume that the individual can consume goods produced both domestically and imported, where imports are combined with domestic goods under the Armington assumption of imperfect substitution (Armington, 1969).

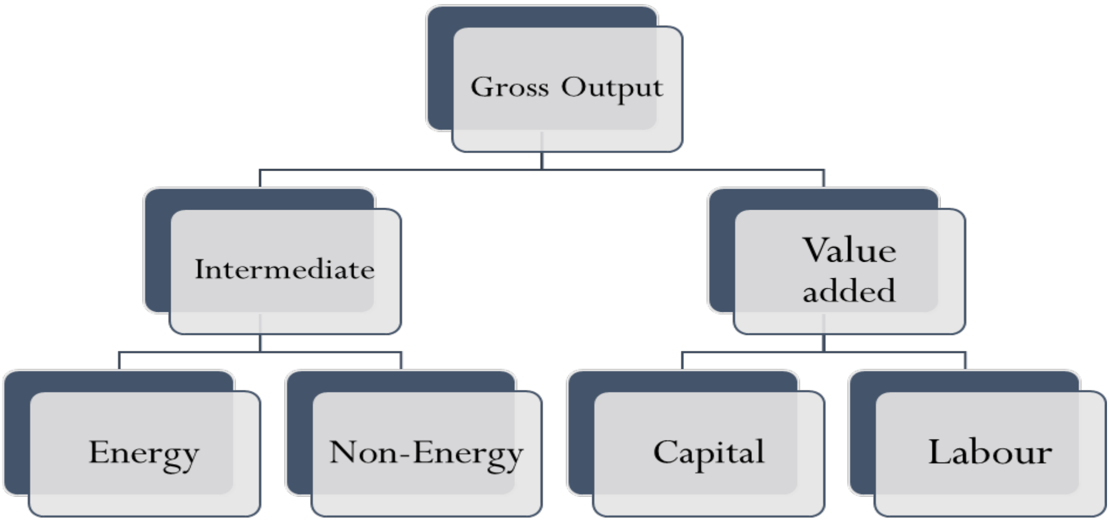
4.2 Production and investment

The production structure is characterised by a capital, labour, energy and materials (KLEM) nested CES function. As we show in Figure1, the combination of labour and capital forms value added, while

[3] We provide the full mathematical description of the model in Appendix B.

energy and materials form intermediate inputs. In turn, the combination of intermediate and value added forms total output in each sector.

Figure 1. The structure of production.



Intermediate composites are produced by a CES production function by a combination of energy (E) and non-energy (NE) inputs:

$$J \;= \left[\delta^{E}(\gamma E)^{\frac{\kappa-1}{\kappa}} + \left(1-\delta^{E}\right)NE^{\frac{\kappa-1}{\kappa}}\right]^{-\frac{\kappa}{\kappa-1}} \qquad (8)$$

In equation (8) κ is the elasticity of substitution between energy and non-energy inputs and γ is the efficiency parameter for energy use in production.

The long run is a conceptual time period, in which all sectoral capital stocks are equal to their desired levels. However, where we run the present myopic model in a period-by-period mode each sector's capital stock is updated between periods via a simple capital stock adjustment procedure, according to which investment equals depreciation plus some fraction of the gap between the desired and actual capital stock.[4] This treatment is wholly consistent with sectoral investment being determined by the relationship between the capital rental rate and the user cost of capital. The capital rental rate is the rental that would have to be paid in a competitive market for the (sector

[4] This process of capital accumulation is compatible with a simple theory of optimal investment behaviour given the assumption of quadratic adjustment costs.

specific) physical capital: the user cost is the total cost to the firm of employing a unit of capital. In sectors where the rental rate exceeds the user cost, desired capital stock is greater than the actual capital stock and there is therefore an incentive to undertake net capital investment. A process of capital decumulation occurs in sectors where rental rates fall below user costs. The resultant capital accumulation (decumulation) puts downward (upward) pressure on rental rates and so tends to restore equilibrium. In the long run, the capital rental rate equals the user cost in each sector, and the rate of return is equalised between sectors.

4.3 Energy prices

We have seen that both theoretical considerations and empirical evidence suggest that energy prices in the UK are likely to be sticky. This reflects both market structure and the pressures from consumers and politicians all of which influences tend to augment the perceived transactions costs of adjusting prices. We illustrate the importance of these considerations in a straightforward way, by assuming that there are quadratic adjustment costs associated with any price change. These costs include, but are not restricted to, simple menu costs. Rather they reflect, in a stylised way, the wider pressures inhibiting full price flexibility. The resultant equation for the energy price is:

$$Pe_t = \lambda Pe^*_t + (1-\lambda)Pe_{t-1} \tag{9}$$

In equation (9), Pe^*_t is the market-clearing level of the energy price and is equal to marginal cost. The simple partial adjustment mechanism indicates that the energy price adjusts only gradually to its market-clearing level. The value of λ can vary between zero and one. Where the value is unity product prices are fully flexible, whilst where they approach zero they become almost rigid. The empirical evidence is not sufficiently compelling to allow us to attach a specific value to λ and, in any case, we wish systematically to explore the impact of the degree of price flexibility on the measurement of rebound effects. Accordingly, we simulate across a range of values of λ and track the impact on rebound.

4.4 The labour market and wage bargaining

As we have already discussed, there are various sources of both nominal and real wage inflexibility. However, here we treat real wage inflexibility and energy price stickiness symmetrically. Accordingly, real wage adjustment is assumed to be subject to adjustment costs that are approximately quadratic in nature; the long-run real wage is driven by a wage bargaining process captured by a wage curve:

$$w_t = \mu w^*_t + (1-\mu)w_{t-1} \tag{10}$$

$$w_t{}^* = \ln\left[\frac{w_t}{cpi_t}\right] = \varphi - \epsilon \ln(u_t) \quad (11)$$

Here the long-run real wage (w*) is determined by the bargaining power of workers and hence the real consumption wage is negatively related to the rate of unemployment (e.g. Blanchflower and Oswald, 2009). In equation (11), $\frac{w_t}{cpi_t}$ is the real consumption wage, φ is a parameter calibrated to the steady state, ε is the elasticity of the wage rate with respect to the rate of unemployment, u. We assume that the population is fixed throughout.

Equations (10) and (11), when combined with the general equilibrium demand for labour (obtained by aggregating over all sectoral labour demands) implies that the real wage adjusts to equate the demand for labour with the amount of labour that wage bargainers are prepared to provide at that wage (which is obtained by substitution of equation (11) into equation (10)). This treatment of the labour market therefore allows for complete real wage flexibility, when $\mu=1$, albeit in the context of an imperfectly competitive labour market that sets the equilibrium real wage above the corresponding competitive level. Of course, for $0<\mu<1$, real wages are less than fully flexible, adjusting only partially to their long-run equilibrium level.

Comparable to our treatment of price flexibility, our simulations explore the sensitivity of rebound to the degree of real wage flexibility (the value of μ).

4.5 Data and calibration

To calibrate the model we follow a common procedure for dynamic CGE models which is to assume that the economy is initially in steady state equilibrium (Adams and Higgs, 1990). We calibrate the model using information from the UK Social Accounting Matrix for 2010.[5] The UKENVI model has 30 separate productive sectors, including 4 main energy supply industries that encompass the supply of coal, refined oil, gas and electricity.[6] We also identify the transactions of UK households, the UK Government, imports, exports and transfers to and from the rest of the World (ROW).

The SAM constitutes the core dataset of the UKENVI model. However other parameter values are required to inform the model. These often specify technical or behavioural relationships, such as production and consumption function substitution and share parameters. Such parameters are either exogenously imposed, based on econometric estimation or best guesses, or determined endogenously through the calibration process.

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[5] The SAM is produced by the Fraser of Allander Institute and available for download at: http://www.strath.ac.uk/business/economics/fraserofallanderinstitute/research/economicmodelling/

[6] See Appendix A, Table A.1 for the full list of sectors and the corresponding sectors in the 2010 UK IO table.

To observe the adjustment of all the economic variables through time, simulations solve for 50 periods (years). We introduce a 5% costless, exogenous and permanent increase in the efficiency of energy used in production by all industries. This implies that the stimulus is applied to the energy composite at the lowest level of the production hierarchy of Figure 1. Results for a range of economic and energy use results are reported for two conceptual periods: the short run, where 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. However, we also report period-by-period values for rate of return on capital and energy rebound effects to allow us to focus on the entire evolution of these variables.

5. Impacts of an improvement in energy efficiency in production

We simulate the impact of the 5% increase in energy efficiency in production under a range of assumptions about the degree of energy price stickiness and real wage inflexibility.

In fact, we find that the extent of rebound is very insensitive to the degree of real wage flexibility, so we do not report these results here.[7] Rather, we focus on the impact of stickiness in the energy price for the scale of rebound effects, assuming our flexible real wage model of the (imperfectly competitive) labour market (μ=1) throughout, so that the real wage is determined in accordance with equation (11).

The impact of the energy efficiency shock on key economic and energy aggregates is summarised in Table 1 for values of λ increasing in increments of 0.1 between 0.1 and 1.0. The figures reported are percentage changes from base for two conceptual time intervals, the short and long run. However, the long-run figures do not vary across values of λ. That is to say, the speed of price adjustment generates no hysteresis effects so that all the models here are converging on the same long-run solution, which we report in the final column of Table 1.

5.1 Long-run impacts

The long-run economic results are as we would expect following a beneficial supply side stimulus in the form of enhanced productivity. There is an increase in competitiveness following a fall in production costs and exports rise by 1.08%. This, together with import substitution, stimulates economic activity and there is also downward pressure on domestic prices. GDP and employment rise by 0.54% and 0.46% respectively, while energy prices and the consumer price index (cpi) fall by 0.32% and -0.54% respectively. There is a corresponding increase in total investment (by 0.66%) and consumption (0.83%) and the unemployment rate falls by -8.66% so that the real wage increases by 0.90% (0.36%+0.54%). The economic expansion is always smaller in the short run. For example, for

[7] Some sensitivity is apparent, but only for extremely low values of λ_1 (<0.01).

the case of λ=1, GDP and employment rise by only 0.17% and 0.27% respectively. In the longer-term, the expansion is enhanced as capacity constraints in energy using sectors are removed and prices fall, stimulating exports, household consumption and investment.

Table 1. The short and long-run impacts of a 5% stimulus to energy efficiency in production (for a range of λ values).

Time period	SR										LR
λ	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	
GDP	0.15	0.16	0.16	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.54
CPI	-0.23	-0.24	-0.24	-0.25	-0.25	-0.26	-0.26	-0.27	-0.27	-0.27	-0.54
Investment	1.12	1.13	1.14	1.15	1.16	1.17	1.18	1.20	1.20	1.20	0.66
Employment	0.25	0.26	0.26	0.26	0.26	0.26	0.27	0.27	0.27	0.27	0.46
Unemployment rate	-4.81	-4.85	-4.89	-4.93	-4.98	-5.01	-5.05	-5.15	-5.15	-5.15	-8.66
Nominal wage	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.36
Household consumption	0.63	0.63	0.64	0.64	0.64	0.64	0.65	0.65	0.65	0.65	0.83
Total export	0.61	0.62	0.62	0.63	0.64	0.64	0.65	0.67	0.67	0.67	1.08
Price of energy	-3.41	-3.47	-3.54	-3.60	-3.66	-3.72	-3.78	-3.87	-3.90	-3.93	-3.32
Price of non-energy	-0.06	-0.06	-0.06	-0.07	-0.07	-0.07	-0.07	-0.08	-0.08	-0.08	-0.39
Household energy	3.94	4.00	4.07	4.14	4.21	4.27	4.33	4.49	4.49	4.49	3.73
Household non-energy	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.45	1.41	1.23	0.67
Intermediate energy	-2.776	-2.75	-2.73	-2.70	-2.68	-2.66	-2.64	-2.58	-2.58	-2.58	-2.68
Intermediate non-energy	0.40	0.40	0.41	0.41	0.41	0.42	-0.07	0.45	1.41	1.23	0.67
Total energy use	-1.01	-0.98	-0.94	-0.90	-0.87	-0.83	-0.80	-0.72	-0.72	-0.72	-0.97
Investment energy	-3.61	-3.61	-3.62	-3.62	-3.62	-3.62	-3.63	-3.63	-3.63	-3.63	-1.67
Investment non-energy	1.34	1.34	1.35	1.36	1.37	1.38	1.39	1.41	1.41	1.23	0.67
Total energy use by non-en sect	-1.89	-1.87	-1.85	-1.82	-1.80	-1.78	-1.76	-1.71	-1.71	-1.71	-1.63
Intermediate rebound	-1.8	-1.4	-0.9	-0.4	0.1	0.5	1.0	2.2	2.2	2.2	46.3
Economy wide rebound	-1.0	-0.1	0.9	1.9	2.9	3.8	4.6	7.0	7.0	7.0	73.4

As already noted there are a number of countervailing forces operating on the total energy use and its component elements, and so on the extent of rebound. First, there is a 3.32% fall in the price of energy measured in natural units, compared to the 0.54% fall in the cpi. This large fall in energy prices reflects the energy intensity of energy production and the reduction in the price of other intermediate inputs. This fall in the relative price generates a 3.73% increase in household energy consumption, as against an increase in total household consumption of 0.83%.

This expansion is offset by a 2.68% reduction in intermediate energy use, which is just over a half of the 5% increase in energy efficiency in production. There is again a substitution of energy for non-energy inputs. The price of intermediate energy when measured in efficiency units falls by 8.32% (3.32% + 5%) and there is also a general increase in economic activity of around 0.5%. Both of these will increase the derived demand for energy intermediates, when measured in efficiency units. However, when these are converted to use measured in physical units, using equation (1), there is a reduction in energy use measured in natural units. This reflects the low imposed elasticity of substitution in production. The net effect of the changes in household energy consumption and intermediate energy demand is a reduction of 0.97% in total energy use. This result indicates that the general equilibrium demand for energy is relatively price-inelastic, for our default parameter values.[8]

Equations (3) and (4) can be used to derive the long-run rebound values for intermediate and total energy use. These are calculated as: R_I = 46.3% and R_T = 73.4%. What is noticeable is the large difference between the two values. Equation (5) reveals that the difference between the two figures hinges on the change in use of energy in non-intermediate uses. Further, we have already noted that there is a relatively large increase in household energy demand, primarily driven by the fall in the price of energy.

5.2 Short-run effects

A central concern of this paper is the short-run rebound effects, their size relative to the corresponding long-run values and the way this is affected by energy price rigidities. The issues are inter-related. However, we begin by comparing the long-run results given in Table 1 with the short-run results where there is complete price flexibility. These are the figures for the value of $\lambda = 1$, which is the standard setting in a CGE model. This means that we are comparing the entries in the final two columns in Table 1.

The first key point is that there are marked differences in the short- and long-run expansion of the economy. GDP, employment and household consumption increase by 0.17%, 0.27% and 0.65% respectively in the short run, but by 0.54%, 0.46% and 0.83% in the long run. These differences are important in terms of economic welfare and would, other things being equal lead an expansion in energy use. However, there are price effects operating in the opposite direction. Energy and non-energy prices fall by 3.93% and 0.08% in the short run. In the long run, the absolute size of the energy price reduction is less, at 3.32%, and the non-energy price reduction is greater, at 0.39%. As argued in the previous section, the fall in the short-run energy price partly reflects excess capacity which is unravelled over time, whilst the price of non-energy commodities falls over time, as capacity constraints are relaxed.

The short-run change in the energy/non-energy relative price differential from the base year values shows a reduction of 3.85% (3.93% - 0.08%); in the long run, this is reduced to 2.93% (3.32% - 0.39%). Clearly the incentive to substitute energy for non-energy consumption and intermediates is

[8] This contrasts with results obtained for Scotland, where there are substantial exports of energy, which are boosted by the fall in energy prices.

greater in the short run than in the long run and this proves large enough to offset any effects of increased activity. Therefore with complete price flexibility, the increase in household energy use, at 4.49%, is greater in the short run than the long run. Similarly, the short-run fall in intermediate and total energy use, at 2.58% and 0.72% respectively, is less than the long-run reductions. The short run intermediate and total rebound effects, at 48.5% and 80.4%, are therefore greater than the corresponding long-run values, replicating the results in Allan et al (2007) and Turner (2009).

Up to now, we have only investigated the conventional short-run results where energy prices are perfectly flexible and take their competitive value in each time period. However, a key focus of the present paper is to determine how far the short-run energy use results are affected by energy price rigidity. This means comparing across the data columns 1 to 10 in Table 1, as the value of λ is gradually increased from 0.1 to 1.0.

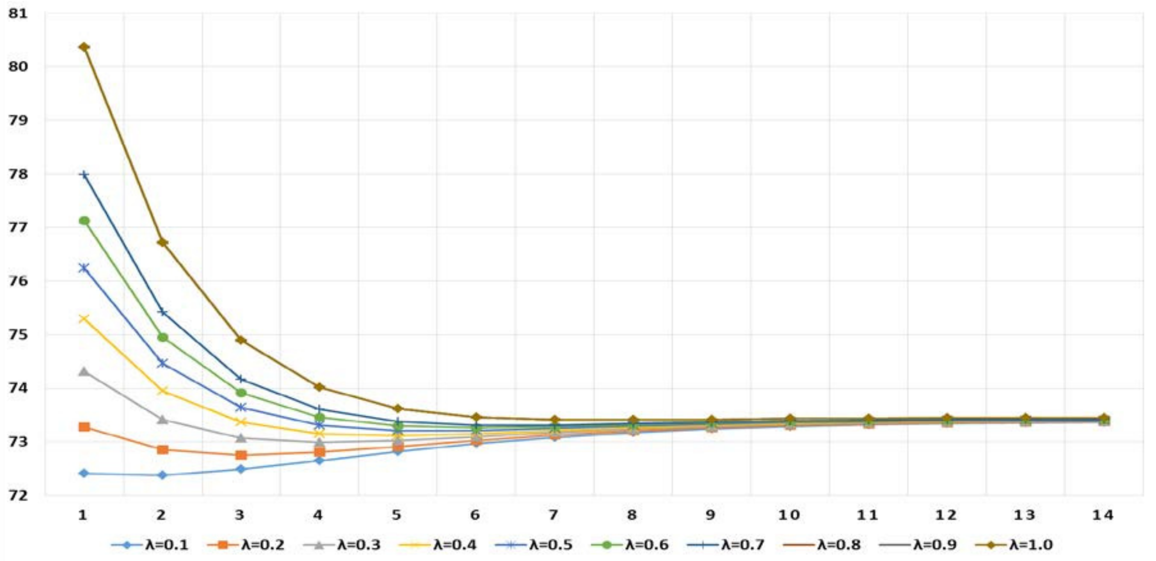
Again to begin with the aggregate economic variables, the impact on short-run GDP, employment and household consumption is relatively limited in percentage point terms. The expansion is lower, in response to more restricted increase in competitiveness, with total exports reduced from a 0.67% increase when λ = 1.0, to 0.61% where λ = 0.1. This lower expansion would itself reduce energy use and therefore rebound. However, more important is the change in relative prices, with energy prices falling by 3.41% at the lowest level of price flexibility as against 3.93% at the highest. The combination of output and substitution effects means that where λ = 0.1, both intermediate and total energy savings are now greater in the short run than in the long run.

The bottom two rows in Table 1 show the absolute long-run rebound values in the final column. However, in the data columns 1 to 10, they report the percentage point difference between the short- and corresponding long-run rebound value. Therefore, for example, in column 6 the short-run intermediate rebound figure is 0.5 percentage points higher than the long-run figure. The absolute short-run intermediate rebound is therefore 46.8% (46.3% +0.5 %) where λ = 0.6. The advantage of presenting the short-run rebound information in this way is that where the values go from positive to negative as the degree of price stickiness increases, this indicates the λ value where the short-run rebound value falls below the corresponding long-run figure. As can be seen from Table 1, this occurs where λ = 0.4 for the intermediate energy use rebound and λ = 0.2 for total rebound.

5.3 Evolution of the energy use

It is interesting to explore the entire time path of rebound effects, rather than simply compare short and long run values. Figure 2 plots the economy wide rebound effects for a range of values of λ. Consider, first, the case of perfect price flexibility. Rebound declines gradually from its short-run level of 80.4% to its long run level of 73.4%. Over time, capacity in the energy sector falls and this limits the extent of the fall in the energy price. This operates quite rapidly initially so that, for example, the period 2 price of energy is -3.65% below the initial level, as compared to -3.93% in period 1. On the other hand, the price of non-energy commodities continues to fall as capacity in energy using sectors expands. These relative price movements reduce the incentive for substitution towards energy.

FIGURE 2. ECONOMY WIDE REBOUND



The changes in capacity are reflected in the changes in the rate of return on capital over time, which are shown in Figure 3 for the case where λ = 1. Note that in period 1, sectors in the energy supply chain, namely mining and quarrying, other mining, crude petroleum, electricity transmission and distribution, and gas all have rates of return below the initial value. In all other sectors there has been an increase. Overtime, these rates return smoothly towards their initial values. This is brought about through a gradual expansion in the non-energy sectors, combined with a contraction of in capacity in the energy sectors. In aggregate economic activity is increasing. In the case of perfect price flexibility the negative substitution effects continue to dominate any expansionary effects, so over time the total rebound falls monotonically and approaches the long-run values from above.

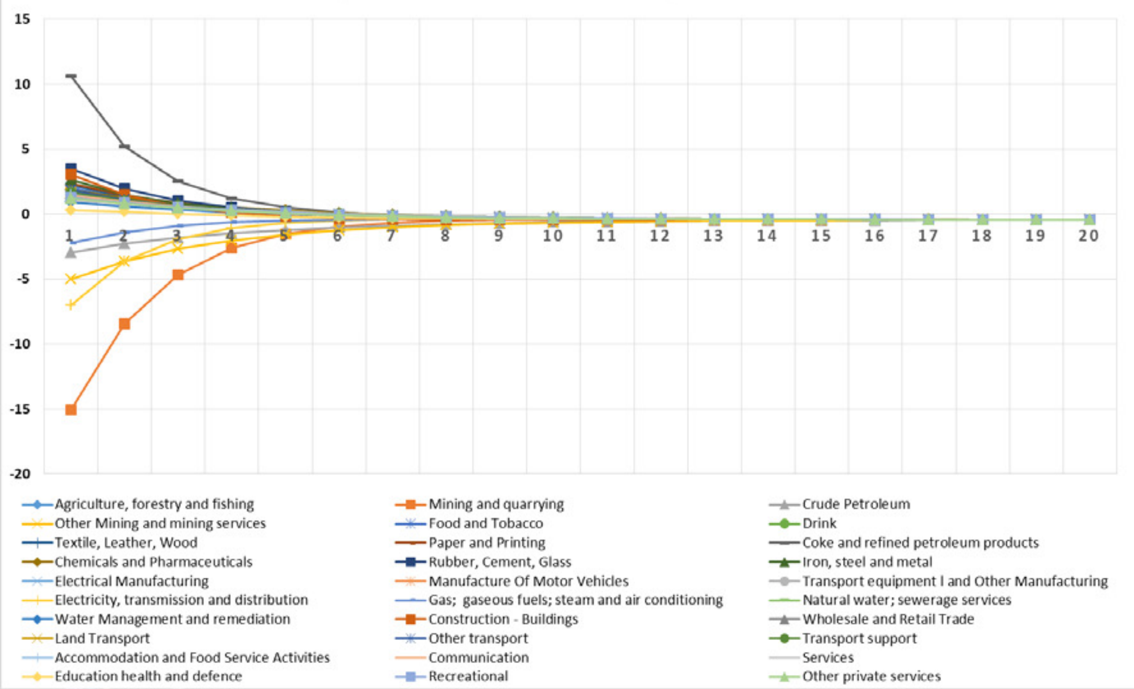


Figure 3. Rate of return on Capital for λ=1

Where the value of λ is at the other extreme and takes the value 0.1 we observe very small adjustments in the price of energy after period 1, together with a slighter greater percentage point reduction in non-energy prices. We therefore observe a gradually increasing rebound value as capacity constraints are reduced in non-energy sectors. However, the variation over time is here very limited, with the total energy rebound value only changing one percentage point over the whole time path. The comparison between short- and long-run sectoral prices and outputs for values of λ equal to 0.1 and 1.0 are shown in Figures 4 and 5.

Figure 4. Sectoral output price changes

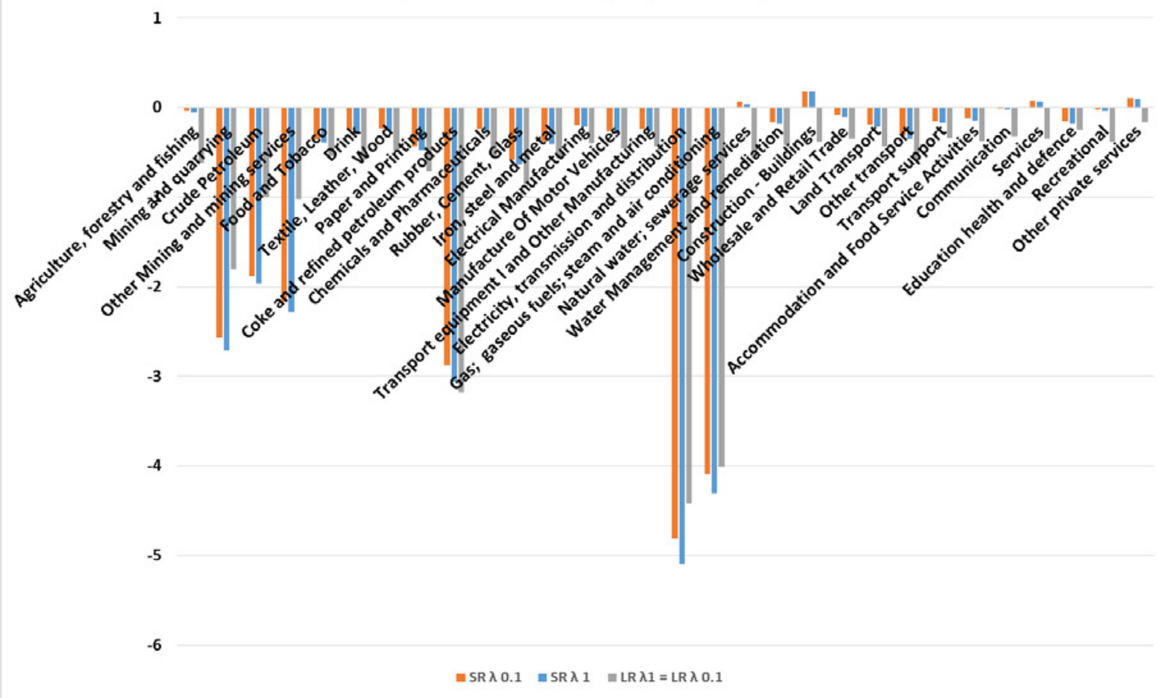
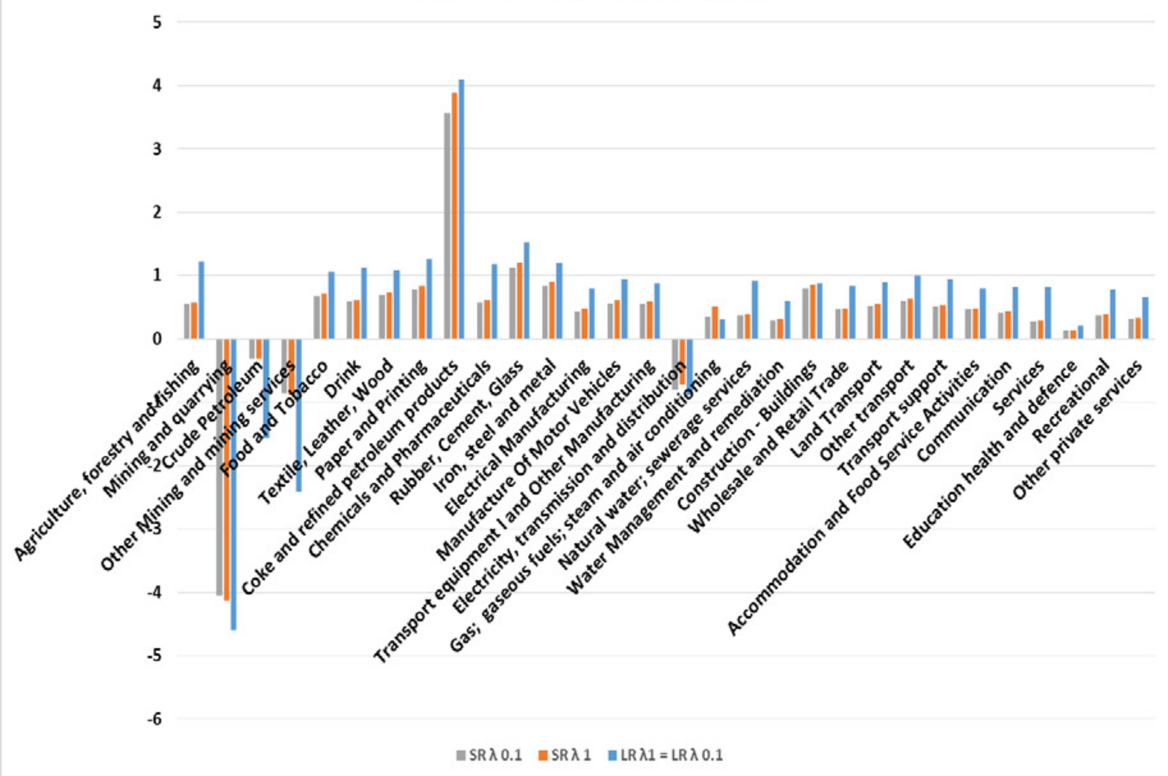


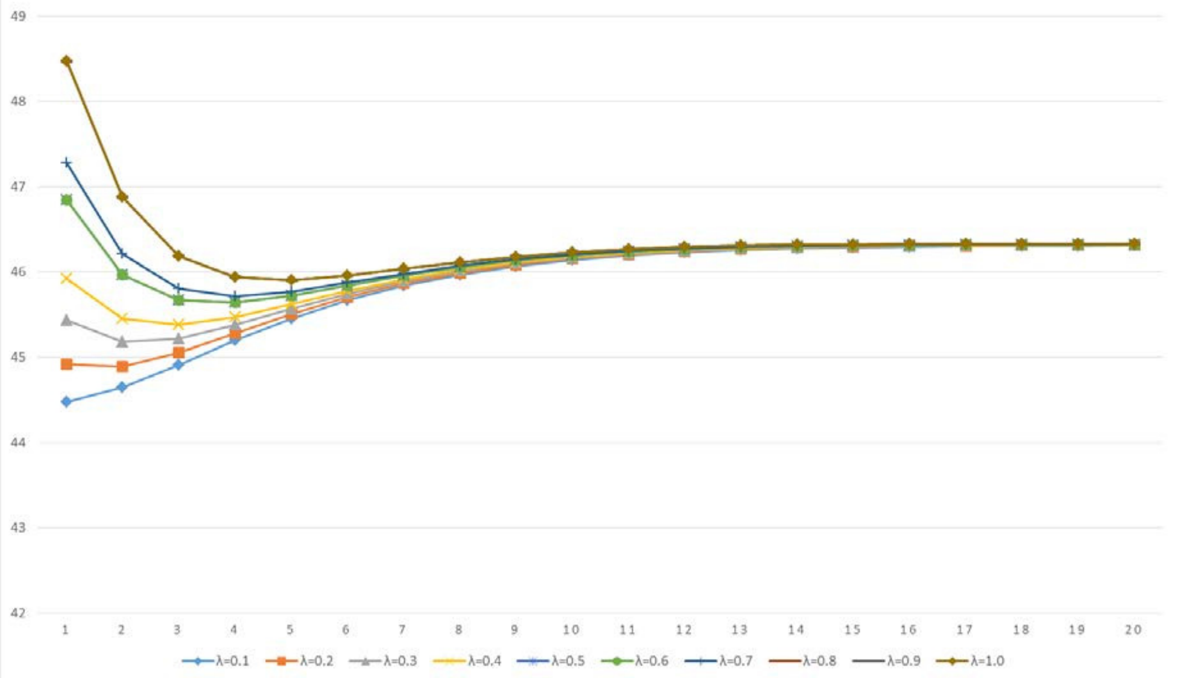
Figure 5. Sectoral output changes



For all degrees of price stickiness between these two extremes a very similar time path of the total energy use rebound is apparent. There is an initial fall in the rebound value below its period 1 level, this leads to a minimum between periods 3 and 8 and then a very gradual increase to the long-run value.

The pattern of change for intermediate energy use rebound in the non-energy sectors, apparent from Figure 6, is broadly similar to that for the system-wide rebound, although the level of rebound is significantly lower, as we have already noted.

FIGURE 6. REBOUND IN INTERMEDIATE ENERGY USE BY NON-ENERGY SECTORS



An important factor is that the elasticity of substitution between energy and non-energy goods in consumption is set at a higher level than in production. This means that energy use in consumption falls continuously over the whole adjustment period, as the substitution effects of the changes in relative prices dominate any income effects. However, in production positive output effects dominate over time so that the rebound values for intermediate energy use all reach a minimum before period 5 and then start to increase.

6. Conclusions

Whilst traditional neoclassical CGE models typically impose perfect price and wage flexibility, there are theoretical arguments and empirical support for a degree of price stickiness in energy markets and wage inflexibility in labour markets. Allan et al (2007) and Turner (2009) each found evidence in of short-run rebound effects that exceed their long-run value, contrary to the theoretical findings of Wei (2007) and Saunders (2008). This was attributed by Turner (2009) to induced price reductions in the energy supply sectors increasing rebound in the short run and subsequent disinvestment in these industries limiting rebound in the longer term. In this paper we systematically explore, for the first time in a CGE context, the impact of price stickiness and real wage inflexibility on the time paths of rebound effects. The shock that we introduce is an increase in energy efficiency in all production sectors.

Our main results are as follows. First, the scale of rebound effects is generally invariant to the degree of real wage inflexibility, where this is defined in terms of the speed of adjustment to the real wage, as given by a standard wage curve. Our empirical analysis therefore focuses on the impact of energy price stickiness under a flexible real wage curve specification.

Second, where the energy price is perfectly flexible, then short-run rebound effects – both for intermediate and total energy use - exceed their long-run values, confirming earlier findings. However, we also establish that this result depends critically on the degree of energy price flexibility. The presence of energy price stickiness can overturn this result, reducing the short-run rebound effects so that they become smaller than the long-run effects.

Third, focussing only on the size of short- and long-run rebound effects omits potentially important detail on the full adjustment paths of energy use. The scale of rebound effects exhibits systematic changes over time that caution against the unguarded use of any estimate of rebound at a particular point in time to inform appropriate energy policy responses. Furthermore, our analysis suggests that very short run measures of rebound are likely to be unreliable indicators of ultimate impacts.

Fourth, our analysis makes it clear that system-wide rebound effects incorporate essential macroeconomic phenomena that microeconomic studies alone are unable to capture. Rebound effects depend on a range of macroeconomic influences, including the degree of energy price stickiness and the complex interaction of transactors, including the energy and non-energy sectors and household demand. Of course, microeconomic studies can provide valuable evidence that may be used to inform appropriate model simulations in a systematic micro-to-macro approach.

There are a number of possible extensions to our analysis including exploring: its importance for the efficiency of energy use in consumption, the main focus of current energy policies; its application to targeted sectoral energy efficiency changes; alternative characterisations of wage and price inflexibility, including drawing more explicitly on models of imperfect competition (and alternative labour market closures); the impact of the government budget constraint, since our simulations imply expanded tax revenues which are not recycled; systematic sensitivity to key substitution and demand elasticities.

We end on a cautionary note. While an understanding of the scale and determinants of rebound effects is important from a policy perspective, energy efficiency policies should be assessed within a wider framework such as the “multiple benefits of energy efficiency” approach proposed by the International Energy Agency (IEA, 2014), rather than focussing exclusively on the scale of energy (and emission) savings. In the present case, the stimulus to production energy efficiency generates a permanent and significant increase in economic activity, which governments would typically value even though this results in smaller energy savings than would otherwise be realised.

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Appendix A

Table A.1. List of production sectors in the UK- ENVI model, corresponding sectors in the 2010 UK IO tables, Standard Industrial Classification (SIC) codes.

Sector name	**SIC**
Agriculture, forestry and fishing	01-03.2
Mining and quarrying	05
Crude petroleum and natural gas + coal	06-08
Other Mining and mining services	09
Food (and tobacco)	10.1-10.9,12
Drink	11.01-11.07
Textile, leather, wood	13-16
Paper and printing	17-18
Coke and refined petroleum products	19-20B
Chemicals and pharmaceuticals	20.3-21
Rubber, cement, glass	22-23other
Iron, steel and metal	24.1-25
Electrical manufacturing	26-28
Manufacture of motor vehicles, trailers etc.	29
Transport equipment and other manufacturing	30-33
Electricity, transmission and distribution	35.1
Gas distribution	35.2-35-3
Water treatment and supply and sewerage	36-37
Waste management and remediation	38-39
Construction-Buildings	41-43
Wholesale and retail trade	45-47
Land and transport	49.1-49.2
Other transport	49.3-51
Transport support	52-53
Accommodation and food and services	55-56,58
Communication	59-63
Services	64-82,97
Education health and defence	84-88
Recreational	90-94
Other private services	95,97

Appendix B. The mathematical presentation of the UK-ENVI model

Prices

$$PM_{i,t} = \overline{PM}_i \qquad \textbf{(B.1)}$$

$$PE_{i,t} = \overline{PE}_i \qquad \textbf{(B.2)}$$

$$PQ_{i,t} = \frac{PR_{i,t} \cdot R_{i,t} + PM_{i,t} \cdot M_{i,t}}{R_{i,t} + M_{i,t}} \qquad \textbf{(B.3)}$$

$$PIR_{j,t} = \frac{\sum_i VR_{i,j,t} \cdot PR_{j,t} + \sum_i VI_{i,j,t} \cdot \overline{PI}_j}{\sum_i VIR_{i,j,t}} \qquad \textbf{(B.4)}$$

$$PY_{j,t} \cdot Y_{j,t} = PX_{j,t} \cdot X_{j,t} - \sum_i PQ_{j,t} \cdot VV_{i,j,t} - IBT_{i,t} \qquad \textbf{(B.5)}$$

$$UCK_t = Pk_t \cdot (r + \delta) \qquad \textbf{(B.6)}$$

$$Pc_t^{1-\sigma^c} = \sum_j \delta_j^f \cdot PQ_{j,t}^{1-\sigma^c} \qquad \textbf{(B.7)}$$

$$Pg_t^{1-\sigma^g} = \sum_j \delta_j^g \cdot PQ_{j,t}^{1-\sigma^g} \qquad \textbf{(B.8)}$$

$$PNE_t = \frac{\sum_z PQ_{z,t} \cdot \bar{V}_z}{\sum_z PQ_z \cdot \bar{V}_z} \qquad \textbf{(B.9)}$$

$$PE_t^* = \frac{\sum_E PQ_{E,t} \cdot \bar{V}_E}{\sum_E PQ_E \cdot \bar{V}_E} \qquad \textbf{(B.10)}$$

$$PE_t = \lambda PE_t^* + (1 - \lambda) PE_{t-1} \qquad \textbf{(B.11)}$$

$$w_t^b = \frac{w_t}{(1 + \tau_t)} \qquad \textbf{(B.12)}$$

$$ln\left(\frac{w_t^b}{cpi_t}\right) = \varphi - 0.068\, ln(u_t) \qquad \textbf{(B.13)}$$

$$rk_{j,t} = PY_{j,t} \cdot \delta_j^k \cdot A^{Y\varrho_j} \cdot \left(\frac{Y_{j,t}}{K_{j,t}}\right)^{1-\varrho_j} \qquad \textbf{(B.14)}$$

$$Pk_t = \frac{\sum_j PQ_{j,t} \cdot \sum_i KM_{i,j}}{\sum_i \sum_j KM_{i,j}} \quad \textbf{(B.15)}$$

Production technology

$$X_{i,t} = A_i{}^X \cdot \left[\delta_i^Y \cdot Y_{i,t}^{\rho_i^X} + \left(1 - \delta_i^V\right) \cdot V_{i,t}^{\rho_i^X}\right]^{\frac{1}{\rho_i^X}} \quad \textbf{(B.16)}$$

$$Y_{j,t} = \left(A^{X\rho_j^X} \cdot \delta_j^Y \cdot \frac{PQ_{j,t}}{PY_{j,t}}\right)^{\frac{1}{1-\rho_j^X}} \cdot X_{j,t} \quad \textbf{(B.17)}$$

$$V_{j,t} = \left(A^{X\rho_j^X}\left(1 - \delta_j^V\right) \cdot \frac{PQ_{j,t}}{Pv_{j,t}}\right)^{\frac{1}{1-\rho_j^X}} \cdot X_{j,t} \quad \textbf{(B.18)}$$

$$V_{j,t} = A^V \cdot \left[\delta_i^V \cdot E_{i,t}^{\rho_i^V} + \left(1 - \delta_i^V\right) \cdot NE_{i,t}^{\rho_i^V}\right]^{\frac{1}{\rho_i^V}} \quad \textbf{(B.19)}$$

$$\frac{E_{j,t}}{NE_{j,t}} = \left[\left(\frac{\delta_j^V}{(1 - \delta_j^V)}\right) \cdot \left(\frac{PNE_t}{PE_t}\right)\right]^{\frac{1}{1-\rho_i^V}} \quad \textbf{(B.20)}$$

$$VV_{z,j,t} = \left(A^{z\rho_j^z}\left(1 - \delta_j^{EN}\right) \cdot \frac{PNE_t}{PQ_{z,t}}\right)^{\frac{1}{1-\rho_j^Z}} \cdot NE_{j,t} \quad \textbf{(B.21)}$$

$$VV_{E,j,t} = \left(A^{E\rho_j^E}\left(\delta_j^{EN}\right) \cdot \frac{PE_t}{PQ_{E,t}}\right)^{\frac{1}{1-\rho_j^E}} \cdot E_{j,t} \quad \textbf{(B.22)}$$

$$Y_{i,t} = A^Y \cdot \left[\delta_i^k \cdot K_{i,t}^{\rho_i^Y} + \delta_i^l \cdot L_{i,t}^{\rho_i^Y}\right]^{\frac{1}{\rho_i^Y}} \quad \textbf{(B.23)}$$

$$L_{j,t} = \left(A^{Y\rho_j^Y} \cdot \delta_j^l \cdot \frac{PY_{j,t}}{w_t}\right)^{\frac{1}{1-\rho_j^Y}} \cdot Y_{j,t} \quad \textbf{(B.24)}$$

Trade

$$VV_{i,j,t} = \gamma_{i,j}^{vv} \cdot \left[\delta_{i,j}^{vm} VM_{i,t}^{\rho_i^A} + \delta_{i,j}^{vir} VIR_{i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad \textbf{(B.25)}$$

$$\frac{VM_{i,j,t}}{VIR_{i,j,t}} = \left[\left(\frac{\delta_{i,j}^{vm}}{\delta_{i,j}^{vir}}\right) \cdot \left(\frac{PIR_{i,t}}{PM_{i,t}}\right)\right]^{\frac{1}{1-\rho_i^A}} \quad \textbf{(B.26)}$$

$$VIR_{i,j,t} = \gamma_{i,j}^{vir} \cdot \left[\delta_{i,j}^{vi} VI_{i,t}^{\rho_i^A} + \delta_{i,j}^{vr} VR_{i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad \textbf{(B.27)}$$

$$\frac{VR_{i,j,t}}{VI_{i,j,t}} = \left[\left(\frac{\delta_{i,j}^{vr}}{\delta_{i,j}^{vi}}\right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}}\right)\right]^{\frac{1}{1-\rho_i^A}} \quad \textbf{(B.28)}$$

$$E_{i,t} = \bar{E}_i \cdot \left(\frac{PE_{i,t}}{PQ_{i,t}}\right)^{\sigma_i^x} \quad \textbf{(B.29)}$$

National Demand

$$R_{i,t} = \sum_j VR_{i,j,t} + \sum_h QHR_{i,h,t} + QVR_{i,t} + QGR_{i,t} \quad \textbf{(B.30)}$$

Total absorption equation

$$X_{i,t} + M_{i,t} = \sum_j VV_{i,j,t} + \sum_h QH_{i,h,t} + QV_{i,t} + QG_{i,t} + E_{i,t} \quad \textbf{(B.31)}$$

Households and other Domestic Institutions

$$YH_t = SHL \cdot LY_t + SHK \cdot KY_t \quad \textbf{(B.32)}$$

$$C_t = YH_t - S_t \quad \textbf{(B.33)}$$

$$LY_t = (1 - \tau_t) L_t^s (1 - u_t) w_t + Trf_t \quad \textbf{(B.34)}$$

$$KY_t = \Pi_t \quad \textbf{(B.35)}$$

$$Trf_t = Pc_t \cdot \overline{Trf} \quad \textbf{(B.36)}$$

$$S_t = mps \cdot [(1 - \tau_t) L_t^s (1 - u_t) w_t + Trf_t] \quad \textbf{(B.37)}$$

$$\Pi_t = \sum_i rk_{i,t} K_{i,t} \quad \textbf{(B.38)}$$

$$QH_{en,t} = H_{en} \cdot \frac{CPI_t}{PE_t} \cdot C_t \quad \textbf{(B.39)}$$

$$QH_{ne,t} = H_{ne} \cdot \frac{CPI_t}{PNE_t} \cdot C_t \quad \textbf{(B.40)}$$

$$QH_{i,t} = \gamma_i^f \cdot \left[\delta_i^{hir} \cdot QHIR_{i,t}^{\rho_i^A} + \delta_i^{hm} \cdot QHM_{i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad \textbf{(B.41)}$$

$$\frac{QHIR_{i,t}}{QHM_{i,t}} = \left[\left(\frac{\delta_i^{hir}}{\delta_i^{hm}}\right) \cdot \left(\frac{PM_{i,t}}{PIR_{i,t}}\right)\right]^{\frac{1}{1-\rho_i^A}} \quad \textbf{(B.42)}$$

$$QHIR_{i,t} = \gamma_i^{fir} \cdot \left[\delta_i^{hr} \cdot QHR_{i,t}^{\rho_i^A} + \delta_i^{hi} \cdot QHI_{i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad \textbf{(B.43)}$$

$$\frac{QHR_{i,t}}{QHI_{i,t}} = \left[\left(\frac{\delta_i^{hr}}{\delta_i^{hi}}\right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}}\right)\right]^{\frac{1}{1-\rho_i^A}} \quad \textbf{(B.44)}$$

Government

$$\overline{FD}_t = GEXP_t - GY_t \quad \textbf{(B.45)}$$

$$GY_t = \left(d^g \cdot \sum_i rk_{i,t} \cdot K_{i,t} + \sum_i IBT_{i,t} + \tau_t \cdot \sum_j L_{j,t} \cdot w_t + \overline{FE} \cdot \varepsilon_t\right) \quad \textbf{(B.46)}$$

$$GEXP_t = G_t \cdot Pg_t + \sum_{dngins} \overline{TRG}_{dngins,t} \cdot CPI_t \quad \textbf{(B.47)}$$

$$QG_{i,t} = \delta_i^g \cdot G_t \quad \textbf{(B.48)}$$

$$QGR_{i,t} = QG_{i,t}; \; QGM_{i,t} = 0 \quad \textbf{(B.49)}$$

Investment Demand

$$QV_{i,t} = \sum_j KM_{i,j} \cdot J_{j,t} \quad \textbf{(B.50)}$$

$$QV_{i,t} = \gamma_i^v \cdot \left[\delta_i^{qvm} \cdot QVM_{i,t}^{\rho_i^A} + \delta_i^{qvir} \cdot QVIR_{i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad \textbf{(B.51)}$$

$$\frac{QVM_{i,t}}{QVIR_{i,t}} = \left[\left(\frac{\delta_i^{qvm}}{\delta_i^{qvir}}\right) \cdot \left(\frac{PIR_{i,t}}{PM_{i,t}}\right)\right]^{\frac{1}{1-\rho_i^A}} \quad \textbf{(B.52)}$$

$$QVIR_{i,t} = \gamma_i^{vir} \cdot \left[\delta_i^{qvi} \cdot QVI_{i,t}^{\rho_i^A} + \delta_i^{qvr} \cdot QVR_{i,t}^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \quad \textbf{(B.53)}$$

$$\frac{QVR_{i,t}}{QVI_{i,t}} = \left[\left(\frac{\delta_i^{qvr}}{\delta_i^{qvi}}\right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}}\right)\right]^{\frac{1}{1-\rho_i^A}} \tag{B.54}$$

Time path of investment

$$I_{i,t} = v \cdot \left(KS_{i,t}^* - KS_{i,t-1}\right) + \delta \cdot KS_{i,t} \tag{B.55}$$

$$KS_{i,t}^* = \left(A^{k^{\rho_j^Y}} \cdot \delta_j^k \cdot \frac{PY_{j,t}}{rk_{i,t}}\right)^{\frac{1}{1-\rho_j^Y}} \cdot Y_{j,t} \tag{B.56}$$

Factors accumulation

$$KS_{i,t+1} = (1 - \delta) \cdot KS_{i,t} + I_{i,t} \tag{B.57}$$

$$K_{i,t} = KS_{i,t} \tag{B.58}$$

$$LS_t \cdot (1 - u_t) = \sum_j L_{j,t} \tag{B.59}$$

Indirect taxes and subsidies

$$IBT_{i,t} = btax_i \cdot X_{i,t} \cdot PQ_{i,t} \tag{B.60}$$

Total demand for import and current account

$$M_{i,t} = \sum_j VI_{i,j,t} + \sum_j VM_{i,j,t} + \sum_h QHM_{i,h,t} + QGM_{i,t} + QVI_{i,t} + QVM_{i,t} \tag{B.61}$$

$$TB_t = \sum_i M_{i,t} \cdot PM_{i,t} - \sum_i E_{i,t} \cdot PE_{i,t} + \varepsilon \cdot \left(\sum_{dngins} \overline{REM}_{dngins} + \overline{FE}\right) \tag{B.62}$$

Steady State conditions

$$\delta \cdot KS_{i,T} = I_{i,T} \tag{B.63}$$

$$R^{k}_{i,T} = \lambda_{i,T}(r + \delta) \quad \textbf{(B.64)}$$

In order to produce short-run results, we have that

$$KS_{i,t=1} = KS_{i,t=0} \quad \textbf{(B.65)}$$

$$LS_{=1} = LS_{t=0} \quad \textbf{(B.66)}$$

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
$h(\subset dngins)$	the set of households
en $(\subset i)$	the set of energy sectors {*Coal, Ele, Gas and Oil*}
ne $(\subset i)$	the set of non-energy sectors

Prices

$PY_{i,t}$	value added price
$PR_{i,t}$	national price
$PQ_{i,t}$	output price
$PIR_{i,t}$	commodity price (national+ REU)
$PI_{i,t}$	price of REU commodities
PE_t	Energy price index
PNE_t	Non-energy price index
$rk_{i,t}$	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
$R_{i,t}$	national supply
$M_{i,t}$	total import
$E_{i,t}$	total export
$Y_{i,t}$	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*
$VR_{i,j,t}$	national intermediate inputs
$VM_{i,j,t}$	ROW intermediate inputs
$VIR_{i,j,t}$	Aggregate intermediate inputs (ROW+REU)
$VI_{i,j,t}$	ROI intermediate inputs
$GEXP_{i,t}$	aggregate government expenditure
$QG_{i,t}$	total government expenditure by sector *i*
$QGR_{i,t}$	national government expenditure
$IBT_{i,t}$	Indirect business taxes
$QGM_{i,t}$	Government import expenditure
$C_{h,t}$	aggregated household consumption
$QH_{i,t}$	total households consumption in sector *i*
$QHR_{i,t}$	national consumption in sector *i*
$QHIR_{i,t}$	national+REU consumption in sector *i*

$QHM_{i,t}$	import consumption in sector *i*
YH_t	Household income
$LY_{i,t}$	Labour income
$KY_{i,t}$	Capital income
SHL	Households share of labour income
SHK	Households share of capital income
$QV_{i,t}$	total investment by sector of origin *i*
$QVR_{i,t}$	national investment by sector of origin *i*
$QVM_{i,t}$	ROW investment demand
$QVIR_{i,t}$	national investment (national+REU)
$QVI_{i,t}$	ROI investment demand
$I_{j,t}$	investment by sector of destination *j*
$J_{j,t}$	investment by destination *j* with adjustment cost
u_t	national unemployment rate
$R_{i,t}^k$	marginal net revenue of capital
S_t	domestic non-government saving
Trf_t	households net transfer
$TRSF_{dngins,dnginsp,t}$	transfer among *dngins*
$\overline{TRG}_{dngins,t}$	Government's transfer to *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
δ	rate of depreciation
v	Adjustment parameter in investment function
λ	Adjustment parameter in price function
H_{en}	Share of household energy consumption
H_{ne}	Share of household non-energy consumption