



Do sticky energy prices impact the time paths of rebound effects associated with energy efficiency actions?

Gioele Figus^a, Peter G. McGregor^a, J. Kim Swales^a, Karen Turner^{b,*}

^a Fraser of Allander Institute, Department of Economics, University of Strathclyde, United Kingdom of Great Britain and Northern Ireland

^b Centre for Energy Policy, University of Strathclyde, United Kingdom of Great Britain and Northern Ireland

ARTICLE INFO

Article history:

Received 21 September 2018
Received in revised form 6 August 2019
Accepted 29 November 2019
Available online 03 January 2020

Keywords:

Energy efficiency
Evolution of energy rebound
Price stickiness

JEL classification:

C68
D58
Q43
Q48

ABSTRACT

There is broad consensus in the policy and academic communities regarding the importance of energy efficiency actions in reducing energy requirements and subsequent greenhouse gas emissions. However, there is also a requirement to understand the extent to which the technically possible energy savings from exogenously introduced efficiency improvements might be eroded by knock-on economic effects which will further change energy use. These effects strongly influence the way this 'rebound' phenomenon evolves over time. While economy-wide drivers of rebound effects are well understood, there has been some controversy over the relative sizes of the short- and long-run rebound effects associated with energy efficiency improvements. Theoretical analysis predicted that rebound effects would always be greater in the long run than in the short run. However, numerical general equilibrium simulations have contradicted this result. A principal driver of the simulation results is the fully flexible response of energy supply prices to shifting demand. However, in practice, there are a number of reasons for arguing that energy prices are likely to be 'sticky'. In this paper we systematically explore the effects of energy price stickiness on the evolution of rebound effects. We find that price stickiness is an important determinant of the time path of rebound effects and of their relative size in the short and long runs. Moreover, there is considerable variation in the scale of rebound effects through time, especially where short-run rebound is lower than its long-run counterpart. However, the most significant overall finding is that rebound reflects the system-wide interaction between energy producing and energy using sectors.

© 2020 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Improving energy efficiency has historically been, and continues to be, promoted as a cost-effective and efficient way to reduce energy demand and greenhouse gas emissions (IEA, 2015; UNEP, 2014; European Council, 2014). However, this view is increasingly accompanied by recognition of the need to understand the extent to which technically possible energy savings associated with increased energy efficiency might be eroded as a result of endogenous direct, indirect and induced impacts on prices and incomes. These impacts affect, and partially redirect, economic activity, making additional changes to energy use through their effect on energy supply and demand. A particular concern of the present paper is to understand how this 'rebound' phenomenon evolves over time, so as to aid the effective design of energy efficiency policy actions. We focus on the need to understand how energy suppliers' price responses to efficiency-driven demand changes may have important implications of interest to – and potentially requiring coordinated planning across – policy

regulators and industry. This is in terms of both the time adjustment of wider economy impacts, and the total energy savings actually delivered.¹

Whilst the drivers of rebound are well understood (e.g. see Turner, 2013, for a review), there has been some controversy over the relative levels of the short- and long-run economy-wide rebound effects accompanying 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.² However, Computable General

¹ We do not explicitly model greenhouse gas emissions in this paper, but existing UK energy generation and use is carbon intensive. Therefore, rebound effects, which limit the effectiveness of energy efficiency improvements in reducing energy use, necessarily diminish the effectiveness of this policy in cutting emissions.

² In this literature, the short and long runs are conceptual time intervals. The short run is an interval over which capital stocks are fixed whilst in the long run capital stocks are optimally adjusted, both in aggregate and in their distribution across industries. As is apparent from the results presented in Section 5 the actual number of simulation periods, assumed to be a year, required for full adjustment depends on the form of the exogenous shock and the size of the values taken by the adjustment parameters.

* Corresponding author.

E-mail address: karen.turner@strath.ac.uk (K. Turner).

Equilibrium (CGE) simulation results reported in Allan et al. (2007) and Turner (2009) contradicted this analytical finding.³ Moreover, using econometric estimation Saunders (2013) found that in aggregate the magnitude of historical direct rebound in the US falls over time, but not for every sector.

The novelty of the paper is that we test, through simulation, how far the higher short-run rebound result for increased energy efficiency in production depends on the assumption of highly flexible prices in the retail energy market. This analysis is carried out at an aggregate and sector by sector level. We also track the evolution of the rebound values as the economy adjusts to the efficiency shock and find that where there is less than perfect price adjustment non-monotonic changes can occur. As far as we are aware, this is the first modelling of gradual price adjustment in a market for produced goods within a CGE context.

The remainder of the paper is organised as follows. Section 2 outlines the way in which energy efficiency improvement are conceptualised in this paper and the cause and nature of long-run system-wide rebound effects. Section 3 identifies the factors that determine the time path of rebound values. Section 4 reviews the relevant literature on price stickiness. Section 5 presents our intertemporal, energy-economy-environment CGE model of the UK economy, with a particular focus on the treatment of price inflexibility. Section 6 reports the simulation results and Section 7 gives brief conclusions.

2. Energy efficiency and the long-run system-wide rebound effect

In this paper we identify through simulation the impact of an improvement in the efficiency with which energy is used as an intermediate input in production, first across all sectors of the economy and then sector by sector. For pedagogic reasons, this efficiency improvement is taken to be exogenous and costless.⁴ We define an increase in energy efficiency as a technological or management improvement that increases the energy services generated by each unit of physical energy (Allan et al., 2007).⁵ This implies that in these functions 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 ψ proportionate increase in energy efficiency:

$$E_f = (1 + \psi)E_p \quad (1)$$

The implication of such an improvement in energy efficiency 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 ψ less physical energy. 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:

$$p_f^e = \frac{p_p^e}{1 + \psi} \quad (2)$$

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

³ Turner (2009) argued that the limitation of the earlier theoretical analyses lay in their assumption of a constant capital rental rate.

⁴ For rebound, the key aspect of an efficiency improvement is the reduction in unit inputs and therefore cost. Accordingly, we assume a costless implementation to the efficiency change itself in order to focus the analysis. Previous work (e.g. Allan et al., 2007) introduced implementation costs but such costs simply add noise in this context. Similarly Lecca et al. (2017) analysed endogenous energy efficiency improvements, in the form of learning curves, but this is outwith the scope of the standard rebound literature.

⁵ Just for complete clarity, in this case the efficiency improvement is limited to where energy is used as an intermediate in production. There is no increase in the efficiency of energy use in final consumption.

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:

$$R_I = \left[1 + \frac{E_{p,I}}{\psi} \right] 100 \quad (3)$$

In Eq. (3) $E_{p,I}$ is the proportionate change in physical energy use in production after the efficiency shock. If this equals the effective increase in total energy productivity, so that $-E_{p,I} = \psi$, 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 affects energy use through two direct - and a number of indirect - channels. The first direct channel is the move to more energy-intensive - as 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, when measured in natural units, is less than the efficiency improvement. The second direct channel is the increased competitiveness of all production sectors experiencing the efficiency improvement. This is driven by the reduced energy costs associated with the direct efficiency increase which, if passed through to product prices, increases the demand for the output of those sectors and the embedded energy used as intermediate inputs.

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 improved competitiveness, are again 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 in 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.

Eq. (3) focusses solely on the use of energy in production but there will also be impacts on the use of energy in final demand. These 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. That is to say, although the change in energy efficiency in production is exogenous, this will necessarily have knock-on economic implications which will further affect energy use. 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 all energy uses, not just use in production. It is defined as:

$$R_T = \left[1 + \frac{E_{p,T}}{\alpha \psi} \right] 100 \quad (4)$$

In Eq. (4), $E_{p,T}$ 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 base-year energy use in production as a share of total energy use. Again, if the percentage reduction in total energy use equals the effective increase in total energy productivity, so that $-E_{p,T} = \alpha \psi$, 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 $E_T/\alpha \psi$ can be expressed as:

$$\frac{E_{p,T}}{\alpha \psi} = \frac{\Delta E_{p,T}}{\psi E_{p,I}} = \frac{\Delta E_{p,I} + \Delta E_{p,C}}{\psi E_{p,I}} = \frac{E_{p,I}}{\psi} + \frac{\Delta E_{p,C}}{\psi E_{p,I}} \quad (5)$$

where Δ represents absolute change and $E_{p,c}$ is energy use in consumption. Substituting Eq. (5) into Eq. (4) and using Eq. (3) gives:

$$R_T = R_I + \left[\frac{\Delta E_{p,c}}{\psi E_{p,1}} \right] 100 \quad (6)$$

Eq. (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.

3. The time path of rebound effects

The discussion in Section 2 reflects the long-run changes that 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. This will also affect the endogenous product prices and therefore energy use. It is these effects which are central to the present paper.

With an efficiency increase the positive substitution, competitiveness and real wage effects which lead to an increase in demand for energy, measured in efficiency units, are restricted in the short run by the fixed capital stock in energy-using industries. Broadly, the argument underpinning higher rebound in the long run rests on capital accumulation relaxing this capacity constraint, stimulating economic activity generally, thereby increasing energy demand, measured in efficiency units, and the size of the rebound effect.

However, capital adjustments with an opposite sign occur in energy-producing industries, generating offsetting effects on energy demand through their impact on energy prices. In the short run, a fall in energy demand, measured in natural units, results in excess capacity in energy-producing sectors. This means that the price of energy, measured in natural units, falls as the result of declining capital rentals: put simply, there is reduced profitability in the energy sectors in the face of declining energy demand. Energy production is capital intensive so that the short-run fall in energy price is large and goes some way to shore up short-run energy production and sales.

Lower profitability leads to disinvestment over time in the energy sectors, with the return on capital eventually being reinstated at the original value. In line with this reduction in capacity, the price of energy, measured in natural units, will also move back towards its initial level. There are therefore two opposing effects: (a) increased demand for energy generated by the short-run reduction in energy prices that results from temporary overcapacity in energy supply sectors, and (b) the long-run expansion in energy demand as the short-run capacity constraints in the energy using sectors are relaxed. Allan et al. (2007) and Turner (2009) find that (a) dominates (b) so that the rebound value in the short run is higher than in the long run.

But this result depends partly upon the flexibility of short-run prices in the energy sector which reflects, at least partly, the assumption of uniform perfect competition imposed in the CGE models used in Allan et al. (2007) and Turner (2009). However, post-Keynesian macro-models argue for the adoption of sticky prices in an imperfectly competitive setting. Further, the UK energy market exhibits a particularly high degree of concentration, especially at the local level. The sector is frequently criticised in the

media and public policy debate for price rigidity, particularly in a downwards direction. The existence of such rigidity would undermine the rationale for a high short-run rebound. In terms of policy implications, understanding the potential price response of energy suppliers is likely to be crucial in understanding what the wider economy response and, thus, rebound effects, of any energy efficiency in any given timeframe may be.

We extend Turner's (2009) analysis by considering the extent to which rebound values are affected by the flexibility of energy prices. As far as we are aware this is the first rebound analysis that explicitly allows for price inflexibilities in the energy supply industry. Further, we study the entire evolution of the rebound effects, not simply their short- and long-run values. This highlights the sensitivity of the rebound value to the precise period in which that measurement takes place and the possible non-monotonic change in energy use following an increase in energy efficiency. These have potentially important result for energy policy.

4. Price stickiness

There is an extensive literature on potential sources of inflexibility that inhibit instantaneous price adjustment to changes in demand and supply conditions. Such price stickiness typically involves 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. For example, 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. Further, in view of its potential significance, there has been considerable efforts to establish theoretical micro-foundations involving price (and wage) inflexibility for New Keynesian macroeconomics. Earlier Keynesian approaches were regarded as incomplete, content to take significant wage and price inflexibility simply as a stylised fact. But the presence of even modest menu costs can give rise to significant price rigidities. These are transactions costs associated with changes in prices, analogous to changing the menus in restaurants.

A second consideration is that large firms typically set prices in a way that would broadly be regarded as fair. Therefore Okun's (1981) notion of "customer" markets, as opposed to auctions, provides a further rationale for firms deviating from conventional short-run profit maximising behaviour, thereby providing a check on rapid price adjustments. If the firm sees its relationship with its customers as important, rapid price changes risk being considered unfair. They undermine customer confidence and encourage their switching 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 subject to limited price competition. 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 (Sweezy, 1939).

These sources of price inflexibility are not necessarily competing and, in practice, price inflexibility could reflect the impact of a range of influences. We are particularly concerned here with prices in the UK wholesale and retail energy markets. This is the price of energy delivered to UK end users for household and industrial use and in such markets a number of these considerations are germane.⁶ The market is oligopolistic in structure with widespread concern about the fairness of any price adjustments. This arises initially among consumers,

⁶ It is important to stress that we are not discussing here price fluctuations in international markets for basic sources of energy such as crude oil.

particularly in relation to the possible abuse of market power, and this spills over into political sensitivity about substantial price adjustments. The market is therefore subject to significant levels of regulation. 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.⁷

Evidence of price stickiness in energy markets has been found in a number of empirical studies. For instance, Bachmeier and Griffin (2003), Farkas and Yontcheva (2019) and Mirza and Bergland (2012) look at the impact of price changes in the US, Hungary and Norway in the wholesale market in responses to changes in costs. They find that there is often a lag in the transmission of cost changes to end user prices. This is especially true in the case of costs reduction.

In the case of the UK, commodity price stickiness is identified in studies by Bunn and Ellis (2011) and Millard and O'Grady (2012). These include some evidence of price inflexibilities in energy markets. However, due to data limitations, their work focuses on prices in the markets for petrol and diesel and therefore does not present a complete picture of price stickiness in the domestic utility market.

In a CGE modelling context, there has been some exploration of the impact of wage inflexibility (see, for example, Böhringer et al., 2013; Dixon and Rimmer, 2011; Partridge and Rickman, 2010). However, no study has focussed on price inflexibilities for a produced product, especially in the context of energy industries.⁸ Accordingly, in this paper we augment our energy, economy, environment CGE model, UKENVI, to capture such behaviour in the energy sector. While there is empirical evidence that supports the presence of price inflexibility in general, and for energy prices in particular (for example Bunn and Fezzi, 2008), we do not estimate such models here. Rather we explore the sensitivity of rebound effects to variation in the degree of energy price stickiness.

5. The CGE model

We simulate the economy-wide and sectoral impacts of improving energy efficiency in all production sectors of the economy using a variant of the Computable General Equilibrium (CGE) model UKENVI. This is a modelling framework constructed for the analysis of economic disturbances to the UK economy, where the ENVI version is specifically designed to study the effects of energy and environmental policies. In the following sections we provide a description of the main characteristics of the model.⁹

5.1. Consumption

In this paper we adopt the myopic version of UKENVI in order to ensure comparability with Turner (2009).¹⁰ Consumption in any period, C_t , is a linear homogeneous function of real disposable income. In each time period, households consume a vector of energy and non-energy goods and services. The energy goods comprise electricity, gas, coal and oil. Households consume both domestically produced and imported goods, where imports are combined

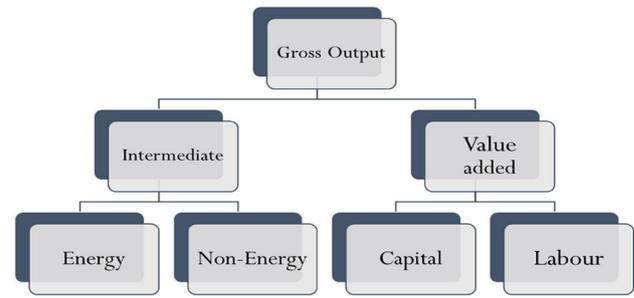


Fig. 1. The structure of production.

with domestic goods under the Armington assumption of imperfect substitution (Armington, 1969).

5.2. Production and investment

The production structure is characterised by a capital, labour, energy and materials (KLEM) nested CES function.¹¹ As shown in Fig. 1, the combination of labour and capital produce value added, while energy and materials form the intermediate inputs. In turn, intermediate and value added combine to generate total output in each sector. Intermediate inputs are either produced domestically, or imported.

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

$$V_{i,t} = \left[\delta_i^V \cdot E_{i,t}^{\rho_i^V} + (1 - \delta_i^V) \cdot ((1 + \psi) \cdot NE_{i,t}^{\rho_i^V}) \right]^{\frac{1}{\rho_i^V}} \quad (7)$$

In Eq. (7), $V_{j,t}$ is the output produced by each industry, j . ρ_i^V is the elasticity of substitution between energy and non-energy inputs (subscript i indicates $N = 1, \dots, I$ inputs produced by each domestic or external industry). δ_i^V is the share parameter, and ψ is the proportionate change to energy efficiency.¹²

The short and long runs are conceptual time periods. In the short run (period 1 of any period by period simulation) the capital stock is fixed, both in aggregate and in its distribution between sectors. The long run is the interval in which the capital stocks in all sectors are fully adjusted and equal to their desired levels. When the present myopic model is run in 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.¹³ 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 specific) physical capital: the user cost is the total cost to the firm of employing an additional 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 reduction occurs in sectors where rental rates fall below user costs. The resultant capital accumulation (reduction) puts downward

⁷ Other potential sources of price stickiness seem less relevant. For example, the capital intensity of the energy industry suggests that wage inflexibility is unlikely, in itself, to be a major explanation of energy price inflexibilities.

⁸ In CGE modelling, adjusting the price of a domestically non-produced input, such as labour or imports, is much more straightforward than intervening in the price adjustment of a domestically produced good.

⁹ A full mathematical description of the model is provided in Appendix B.

¹⁰ We have run an alternative scenario in which forward-looking agents determine both investment and consumption expenditures. In both the myopic and forward-looking simulations the short-run and transition path results are qualitatively similar and converge to the same long-run equilibrium.

¹¹ We set the elasticity of substitution to 0.3 and the Armington elasticity to 2 as in Turner (2009). This ensures the comparability of results. The sensitivity of results to a range of elasticity values is tested extensively in Turner (2009), Section 5.

¹² ψ is initially calibrated to be equal to zero. In the simulations reported in Section 6 we set ψ to 0.05 to replicate a 5% increase in energy efficiency.

¹³ This procedure is compatible with a simple theory of optimal investment behaviour given the assumption of quadratic adjustment costs.

(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 to capital is equalised between sectors.

5.3. Energy prices

As argued in Section 2, both theoretical considerations and empirical evidence suggest that energy prices in the UK are likely to be sticky. However, standard general equilibrium models assume that at any time period prices equal the desired market clearing level,¹⁴ which is equal to the marginal cost. In the UKENVI model, the energy price is defined generically as follows:

$$pe_t^* = pe_t(w_t, rk_t, pr_t, \overline{pm}) \quad (8)$$

In Eq. (8), w is the nominal wage, rk is the capital rental rate, pr is the price of domestic intermediate and pm is the price of imported intermediates, which is the numeraire. To illustrate the importance of stickiness in price adjustments we assume that there are quadratic adjustment costs associated with any price change. This is implemented by replacing Eq. (8) with the following:

$$pe_t = \lambda pe_t^* + (1-\lambda)pe_{t-1} \quad (9)$$

Eq. (9) implies that in any time period, t , the energy price is the weighted sum of the current market clearing price from eq. (8) and the price in the previous period, $t - 1$. The simple partial adjustment mechanism indicates that the energy price adjusts only gradually to its desired 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 λ approaches zero they become almost rigid along the transitioning path. 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.

5.4. The labour market and wage bargaining

In the labour market, the real wage, $\frac{w_t}{cpi_t}$, is determined by Eq. (10):

$$\ln \left[\frac{w_t}{cpi_t} \right] = \varphi - \epsilon \ln(u_t) \quad (10)$$

There is extensive empirical evidence for this wage curve specification. The standard justification for which is that the real wage is determined by the bargaining power of workers which is stronger when the rate of unemployment, u , is low (Blanchflower and Oswald, 2005). The parameter φ is calibrated to the steady state and ϵ the imposed elasticity of the wage rate with respect to the rate of unemployment (Blanchflower and Oswald, 1994). We assume that the population is fixed throughout, making the analysis again consistent with Turner (2009).¹⁵

¹⁴ We use the term “desired market clearing” because in each time period the energy markets do clear in the sense that industry suppliers meet the demand at the price set. There is no rationing. However, this is not a short-run profit-maximising output for individual firms and the price is not the short-run competitive price.

¹⁵ The population could be updated endogenously by introducing migration between the UK and the rest of the World. Our assumption of a fixed population is standard in national CGE models.

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	Short run						Long run
	λ	0.2	0.4	0.6	0.8	0.9	
GDP	0.09	0.11	0.12	0.14	0.15	0.17	0.54
CPI	-0.01	-0.05	-0.11	-0.18	-0.23	-0.27	-0.54
Investment	0.72	0.81	0.91	1.03	1.11	1.20	0.66
Employment	0.15	0.17	0.20	0.23	0.25	0.27	0.46
Unemployment rate	-2.91	-3.31	-3.79	-4.39	-4.74	-5.15	-8.66
Nominal wage	0.29	0.28	0.28	0.27	0.63	0.26	0.36
Households							
consumption	0.50	0.53	0.56	0.60	0.63	0.65	0.83
Exports	0.31	0.38	0.45	0.54	0.60	0.66	1.08
Price of energy	-0.51	-1.11	-1.85	-2.76	-3.31	-3.93	-3.32
Price of non-energy	0.02	0.00	-0.02	-0.04	-0.06	-0.08	-0.39
Household energy	1.01	1.61	2.34	3.27	3.84	4.49	3.73
Household non-energy	0.47	0.47	0.47	0.46	0.46	0.45	0.68
Intermediate energy	-3.85	-3.63	-3.36	-3.02	-2.81	-2.58	-2.68
Intermediate non-energy	0.26	0.29	0.32	0.37	0.39	0.43	0.75
Total energy use	-2.57	-2.25	-1.86	-1.36	-1.06	-0.72	-0.97
Investment energy	-3.98	-3.94	-3.87	-3.79	-3.74	-3.67	-0.88
Investment non-energy	0.76	0.84	0.94	1.07	1.14	1.23	0.67
Sectoral rebound impact	23.01	27.39	32.78	39.58	43.71	48.46	46.30
Economy wide rebound impact	29.71	38.41	49.13	62.67	70.88	80.35	73.36

5.5. Data and calibration

The primary source for model calibration is the UK Social Accounting Matrix (SAM) for 2010. 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). 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.¹⁶ 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.

5.6. Simulation strategy

We introduce an exogenous 5% permanent step increase in the efficiency of energy used in production by all industries in period 1. This is done by setting the parameter ψ in Eq. (7) to 0.05. The efficiency stimulus is applied to the energy composite at the lowest level of the production hierarchy shown in Fig. 1. In each simulation the model is then run forward for 50 periods (years). In one set of simulations the increase in energy efficiency is applied to all sectors simultaneously. Results are reported for the short- and long-run values for a set of key energy and economic variables over a range of values for the energy price stickiness parameter λ . The time paths of intermediate and total energy use rebound values are also shown. We then follow exactly the same procedure but introduce the increase the energy efficiency in each individual productive sector so that 30 sector specific sets of simulations are performed.

¹⁶ See Appendix A, Table A.1 for the full list of sectors and the corresponding sectors in the 2010 UK IO table.

6. Impacts of an improvement in energy efficiency in production

The impact of the energy efficiency shock on key economic and energy aggregates is summarised in Table 1. Results are reported for two conceptual periods: the short run and the long run. Recall that the short run is the initial period after the efficiency shock, where capital stocks are fixed both in aggregate and in their sectoral composition. The long run corresponds to the new steady state equilibrium characterised by no further changes in sectoral capital stocks.

For the short run, results from six variants of the model are reported. These are where the λ coefficient takes values between 0.2 and 1.0. Whilst the speed at which the economy approaches long-run equilibrium does depend on the value of λ , the ultimate long-run figures do not. That is, the speed of price adjustment generates no hysteresis effects so that all the models here converge on the same long-run solution. Consider first the long-run results.

6.1. Long-run impacts

The long-run economic impacts are reported in the final column in Table 1, which are given, as are all the figures in this table, as percentage changes from the initial values. The results are as expected following a beneficial supply-side stimulus in the form of enhanced productivity. There is an increase in competitiveness following the fall in production costs so that exports rise by 1.08%. This, together with substitution away from imports, stimulates economic activity and there is also downward pressure on domestic prices. GDP and employment rise by 0.54% and 0.46% respectively and there is an accompanying increase in total investment and consumption. The level of unemployment (and therefore also the unemployment rate) falls by 8.66% so that the real wage increases by 0.90% (given by the nominal wage minus the change in the CPI, i.e. 0.36% + 0.54%).

Focussing on the total long-run energy use and its component elements, a number of countervailing forces are in operation. First, there is a 3.32% fall in the price of energy measured in natural units, compared to the 0.54% fall in the consumer price index (cpi), reflecting the energy intensity of energy production and the reduction in the price of other intermediate inputs. Therefore whilst energy efficiency in household consumption has not changed, the relative reduction in energy prices means that household consumption becomes more energy intensive. There is a 3.73% increase in the consumption of energy by households, as against the increase in total household consumption of 0.83%.

The price of intermediate energy, when measured in efficiency units, falls by a greater amount, 8.32%. This is the sum of the 3.32% fall in energy prices measured in natural units, together with the 5% increase in efficiency. There is again a substitution of energy, in efficiency units, for non-energy inputs, 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 physical units, using Eq. (1), there is a reduction in energy use of 2.68%, just over a half of the 5% increase in energy efficiency 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.

Eqs. (3) and (4) can be used to derive the long-run rebound values for intermediate and total energy use. These are calculated as: $R_I = 46.30\%$ and $R_T = 73.36\%$. There is a large difference between the two values. Eq. (5) reveals that this 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 measured in natural units.

6.2. Short-run impacts: $\lambda = 1$

We begin by comparing the long-run results given in Table 1 with the short-run figures where there is complete price flexibility. These are the results 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 observation is that there are marked differences in the short- and long-run expansions of the economy. The economic expansion is smaller in the short run than in the long run; short-run GDP, employment and household consumption rise by only 0.17%, 0.27% and 0.65% respectively. In the longer term, the expansion is enhanced as capacity constraints in energy using sectors are removed and prices fall, further stimulating exports, household consumption and investment.

These differences are important in terms of economic well-being and would, other things being equal, lead to higher energy use in the long run than in the short run. However, as described in Section 3, 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%. The fall in the short-run energy price partly reflects excess capacity, a situation that unravels 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 fall of 3.85% (3.93% minus 0.08%); in the long run this is reduced to 2.93% (3.32% minus 0.39%). The incentive to substitute energy for non-energy commodities in consumption and intermediate use is 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 falls in intermediate and total energy use, at 2.58% and 0.72% respectively, are less than the long-run reductions in the same aggregates. We therefore replicate with a later data set the results reported by Allan et al. (2007) and Turner (2009). Under standard pricing assumptions, the short-run intermediate and total rebound effects, at 48.46% and 80.35%, are greater than the corresponding long-run values.

6.3. Short-run impacts: $\lambda < 1$

In the previous sub-section we presented the conventional short-run results. These derive from a simulation in which energy prices are perfectly flexible and in each time period take their competitive values. 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 6 in Table 1, as the value of λ is gradually increased from 0.2 to 1.0.¹⁷

Again we begin with the aggregate economic figures. The impact of varying the degree of energy price flexibility on the short-run percentage change in GDP, employment and household consumption is limited. The smaller is λ , that is, the stickier energy prices are, the lower is the short-run economic expansion, reflecting the more restricted improvement in competitiveness. For example, the increase in total exports is reduced from 0.66% when $\lambda = 1.0$ to 0.31% where $\lambda = 0.2$. This in itself would reduce short-run energy use, and therefore rebound, as λ fell. However, more important is the change in relative prices, with energy prices falling by 0.51% at the lowest level of price flexibility as against 3.93% at the highest. In fact for all values of

¹⁷ We do not report the results for the value of $\lambda = 0$. In that case, the energy price would essentially be set exogenously. This leads to problems of rationing when costs or demand conditions change, an issue beyond the scope of the present paper and not germane to the rebound literature.

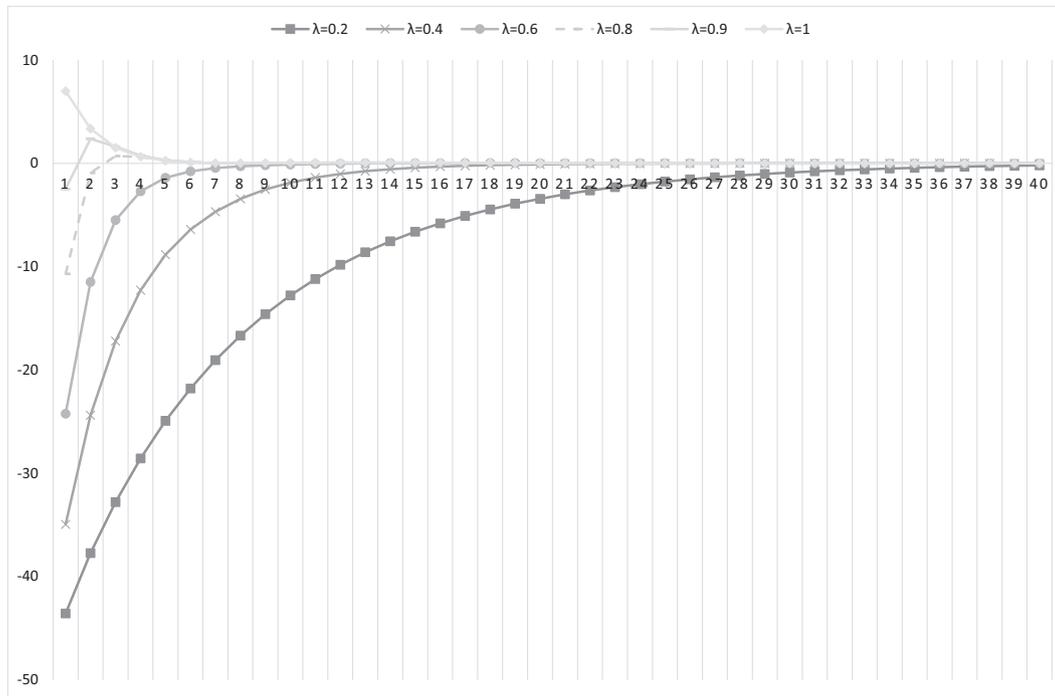


Fig. 2. Percentage point difference between period by period and long run economy wide rebound from a 5% increase in energy efficiency in intermediate energy use.

$\lambda \leq 0.8$ the short-run relative reduction in energy prices is less than in the long run. This has the implication that for $\lambda \leq 0.8$, both intermediate and total energy savings are now greater in the short run than in the long run.

In the bottom two rows in Table 1, the final column translates this to report the long-run rebound values for industrial (sectoral) and total (economy-wide) energy use. As stated earlier, the long-run sectoral and total rebound values are 46.3% and 73.36% respectively. The first six columns of Table 1 give corresponding short-run rebound values as the λ value increases. The key result is that when $\lambda \leq 0.8$, the short-run rebound is lower than the long-run rebound. That is to say, with a slower price adjustment in the energy sector, the apparently anomalous result that the rebound is greater in the short run than the long run no longer holds. The most extreme case recorded in Table 1 is for $\lambda = 0.2$, where the economy-wide rebound is 29.7% which is 43.7 percentage points smaller than the long run.

6.4. Evolution of energy use

It is interesting to explore the entire time path of rebound effects, rather than simply compare short- and long-run figures. We therefore report period-by-period values for energy rebound and sectoral rates of return on capital so as to focus on the entire evolution of these variables. We begin with economy-wide rebound results which are shown in Fig. 2. This plots the difference between the economy-wide rebound figure in each period and the long-run figure; that is to say, if the value in Fig. 2 for any time period is positive (negative), the rebound in that period is greater (less) than the long-run value. The different curves represent the results for different values of λ , varying between 0.2 and 1.0.

Consider, first, the case of perfect price flexibility, $\lambda = 1.0$. In period 1, economy-wide rebound is at its short-run level of 80.35%, 6.99% above the long-run value of 73.36%. Over time, capacity in the energy sector falls, limiting the extent of the reduction 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. This means that the economy-wide rebound moves monotonically towards the long-run value and is very close by period 7.

The changes in capacity reflect, and are reflected in, changes in the sectorally disaggregated rates of return on capital over time. These are shown in Fig. 3 for the simulation where $\lambda = 1$. 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 well below their base-year values. All other sectors experience an increase. Overtime, these rates move smoothly back towards their initial values. This is brought about through a gradual expansion of capacity in the non-energy sectors, combined with a contraction of capacity in the energy sectors. In aggregate, economic activity is still increasing.¹⁸

Any energy price stickiness limits the initial fall in energy prices in response to overcapacity in the energy sector. This reduces the rebound values in the early periods. Where the degree of stickiness is high, so that the value of λ is low, the impact of the excess capacity is effectively suppressed; where λ is closer to 1, the situation is more nuanced.

In the simulation that uses a value for λ of 0.6, we observe a gradual fall in the price of energy from a reduction of 1.85% in period 1 to a decline of 3.32% in the long run, together with a slow reduction in non-energy prices. Fig. 2 therefore reports a gradually increasing rebound value over time as capacity constraints are reduced in non-energy sectors. When λ takes the value 0.2, this gradual adjustment is even more extreme, with it taking over 40 years for rebound to reach its long-run value.

¹⁸ Figures C1 and C2 in Appendix C provide a comparison between short- and long run sectoral prices and outputs for values of λ equal to 0.1 and 1.0.

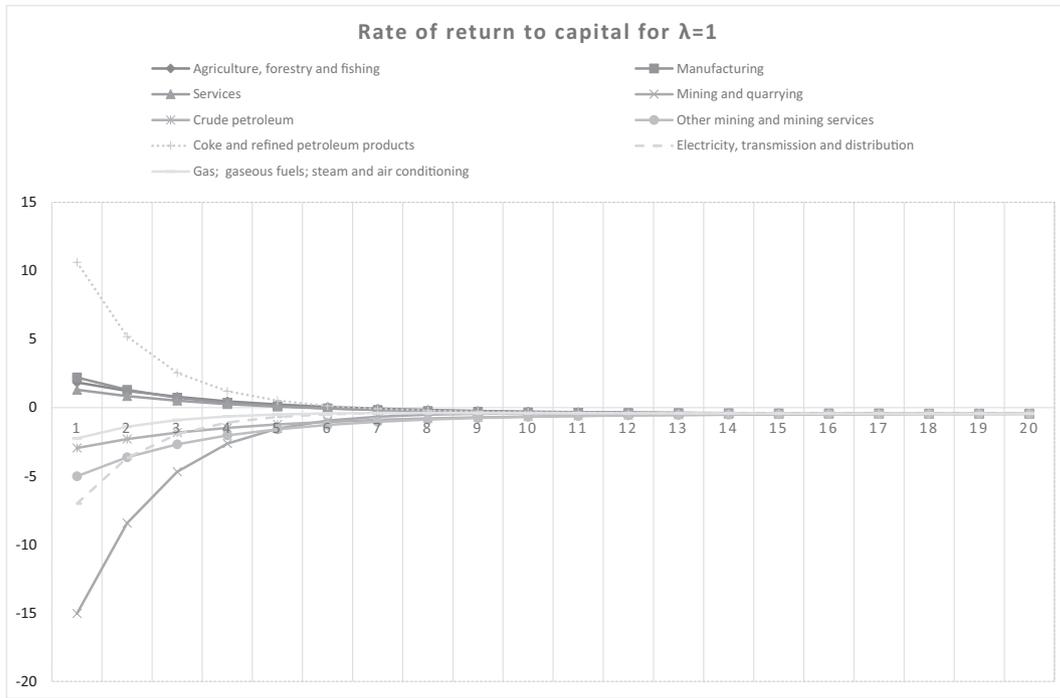


Fig. 3. Sectoral rate of return to capital for $\lambda = 1$.

However, for λ values of 0.8 and 0.9, the rebound adjustment is non-monotonic. Whilst the short-run rebound is below the long-run value there is subsequent overshooting as the economy adjusts to the energy efficiency shock. For $\lambda = 0.9$, the initial rebound is slightly below the long-run figure. However, continuing adjustment in energy prices to overcapacity further stimulates the demand for energy so that in period 2 the rebound is above, by 2.5

percentage points, the long-run value. From period 3 onwards rebound falls smoothly, converging on the long-run value from above. A similar pattern is apparent when $\lambda = 0.8$. Here in the first two periods rebound is below, but subsequently above, the long-run value.

Fig. 4 presents the evolution of rebound in intermediate energy use, similar to the whole-economy figures represented in Fig. 2. The

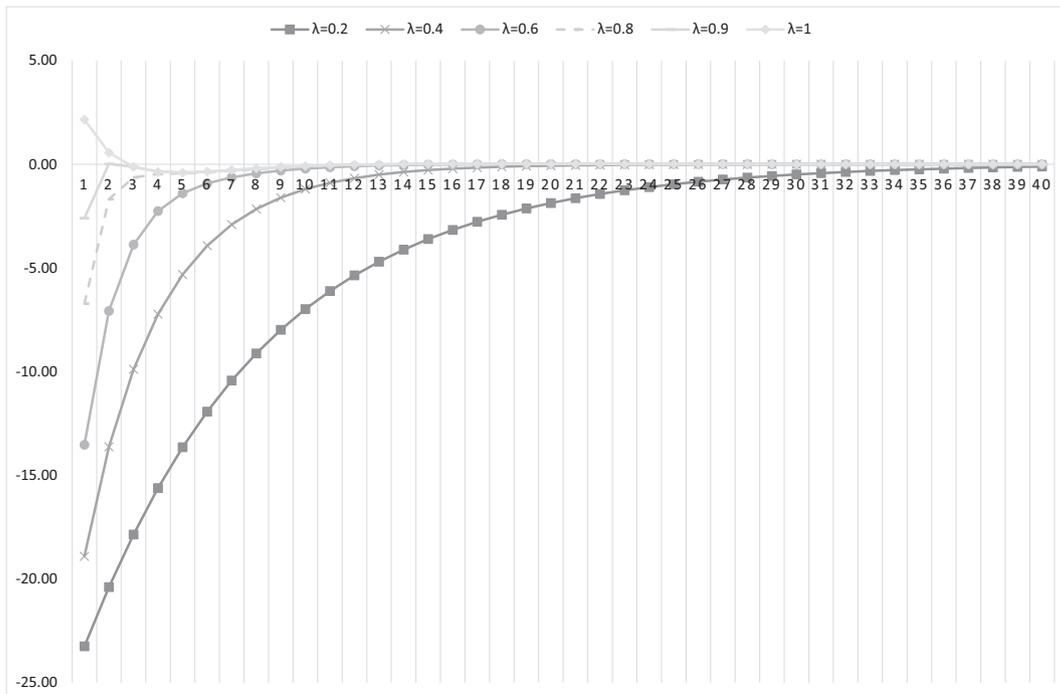


Fig. 4. Percentage point difference between period by period and long run rebound in intermediate energy use.

patterns of change are broadly similar, although, as has already been noted, both short- and long-run intermediate energy rebound values are substantially lower. It is interesting to note that even when $\lambda = 1$, rebound in intermediate energy use falls slightly below its long-run value from period 3 and continues to fall until period 5, after which it begins to rise, approaching the long-run value asymptotically from below. The distinctive time path of whole-economy rebound observed for $\lambda = 0.9$ is also apparent for intermediate rebound. However, where $\lambda = 0.8$, the rebound value now monotonically approaches the long-run value from below.

It is clear from our analysis that a simple comparison of short- and long-run values of both intermediate and total rebound effects is potentially misleading. It is of value to know the speed of adjustment to the long-run values but also that the adjustment paths may be non-monotonic, particularly where price flexibility is high.

6.5. Sectoral rebound values

In the preceding sub-sections we have analysed in detail the rebound results following improvements in energy efficiency which apply simultaneously to all sectors of the economy. This is primarily to set the work in the context of previous studies by Allan et al. (2007) and Turner (2009). In this sub-section we briefly consider whether the same factors apply where the efficiency improvement occurs in just one sector. That is to say; is the short-run rebound typically higher than the long-run value and is this result sensitive to the degree of price stickiness in the energy sector?

In order to test these propositions we introduce a 5% increase in energy efficiency in production in each sector, one sector at a time. We calculate the short- and long-run all-economy rebound results, in a similar manner as in Sections 6.1, 6.2 and 6.3. The rebound results for all 30 sectors and for price adjustment parameters varying between 0.1 and 1.0 are reported in Table D1 in Appendix D.

In the conventional case, in which there is no price stickiness in the energy market so that $\lambda = 1$, the short-run rebound is greater than the long-run value in 26 of the 30 industries. The four industries where this is not the case are linked to the energy sector itself. These sectors are: "Mining and quarrying", "Crude petroleum, natural gas etc.", "Other mining" and "Coke and refined petroleum products".

For all individual-industry simulations, reducing λ reduces the difference between the short- and long-run rebound values. For the 26 industries where the initial difference is positive, at some value of λ this turns negative in 20 sectors. Those sectors which still have short-run rebound greater than long-run where λ takes its smallest value, 0.1, all have differences that are very small. They are primarily service sector industries.¹⁹ These results taken as a whole imply that the economy-wide energy use response to energy efficiency improvements in two thirds of all individual sectors is qualitatively similar to the response to an aggregate efficiency improvement.

7. Conclusions

Whilst traditional neoclassical CGE models typically impose perfect price flexibility, there are theoretical arguments and empirical support for a degree of price stickiness in energy markets. Moreover, policy debates reflect concern over a range of issues around energy pricing, which suggests a need for revisiting fundamental assumptions employed in CGE and other economic models. The novelty of the current paper is the focus on the impact of price inflexibility in energy

markets on the time-path of rebound in energy use, and to explain this in the context of the wider economic expansion triggered by industrial energy efficiency gains. This is an important lens for policy makers to consider the wider impacts of increased energy efficiency through, given that it may imply a requirement for coordinated planning across policymakers, regulators, industry energy users and energy suppliers in order to maximise both net economic gains and energy savings.

Our main results are as follows. First, 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 simulation findings. However, we also establish that this result depends critically on the degree of energy price flexibility. That is to say, 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.

Second, 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.

Third, these results apply generally where the increase in energy efficiency applies only to one sector. In over 85% of all sectors the short-run economy-wide rebound effects were greater than the long-run values and in over 65% this was also reversed at some level of energy price stickiness.

Fourth, and crucial in terms of the policy context of rebound research, 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. This is not to dispute the fact that microeconomic analysis is essential, not least to provide valuable evidence that may be used to inform appropriate economy-wide model simulations in a systematic micro-to-macro approach.

There are a number of straightforward possible extensions to our analysis. First, particularly given the focus of many policy actions on residential energy efficiency (including, but not limited to, impacts on fuel poverty), it would be useful to extend our analysis to the efficiency of energy use in consumption. Second, and perhaps more importantly, the results show that the time path of rebound impacts depends crucially on the interaction between simultaneously expanding and contracting economic sectors. The work reveals that just changing the speed of price adjustment in one key sector has an important impact on the evolution over time of the economy's response. We wish to extend the work here to consider more widely variations in not only price stickiness across sectors but also capacity adjustments. This would be valuable for the analysis of both economy-wide and sector-specific shocks.

Acknowledgements

The research reported in this paper was funded by the UK Engineering and Physical Sciences Research Council (EPSRC grant ref. EP/M00760X/1). We also acknowledge the support of ClimateXChange, the Scottish Government-funded Centre for Expertise in Climate Change, whilst noting that the opinions in the paper are the sole responsibility of the authors, and not necessarily those of the ClimateXChange or the Scottish Government. We are grateful to two unknown referees for their useful comments. All data supporting this research are openly available at <https://doi.org/10.15129/a5cb18a4-bcd0-40bf-a6ea-fa738bfc2613>.

¹⁹ The sectors are: "Natural water treatment, etc.", "Wholesale and retail", "Transport support", "Services", "Recreational" and "Other private services".

Appendix A

Table A1

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

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

$$PEX_{i,t} = \overline{PEX}_i \quad (B.2)$$

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

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

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

$$UCK_t = Pk_t \cdot (r + \delta) \quad (B.6)$$

$$CPI_t = \frac{QH_{en,t} \cdot pe_t + QH_{ne,t} \cdot PNE_t}{C_0} \quad (B.7)$$

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

$$PNE_t = \frac{\sum_{ne} PQ_{ne,t} \cdot \overline{V}_{ne}}{\sum_{ne} PQ_{ne} \cdot \overline{V}_{ne}} \quad (B.9)$$

$$pe_t^* = \frac{\sum_{en} PQ_{en,t} \cdot \overline{V}_{en}}{\sum_{en} PQ_{en} \cdot \overline{V}_{en}} \quad (B.10)$$

$$pe_t = \lambda pe_t^* + (1-\lambda) pe_{t-1} \quad (B.11)$$

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

$$\ln\left(\frac{w_t^b}{CPI_t}\right) = \varphi - 0.068 \ln(u_t) \quad (B.13)$$

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

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

Production technology

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

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

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

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

$$E_{j,t} = \left[(1 + \psi) \rho_j^V \cdot \delta_i^V \cdot \left(\frac{PY_{j,t}}{pe_t} \right) \right] \frac{1}{1 - \rho_j^V} \quad (\text{B.20})$$

$$NE_{j,t} = \left[A_{NE}^V \rho_j^V \cdot (1 - \delta_i^V) \cdot \left(\frac{PY_{j,t}}{PNE_t} \right) \right] \frac{1}{1 - \rho_j^V} \quad (\text{B.21})$$

$$VW_{z,j,t} = \left((1 - \delta_j^{EN}) \frac{PNE_t}{PQ_{z,t}} \right) \frac{1}{1 - \rho_j^Z} NE_{j,t} \quad (\text{B.22})$$

$$VW_{E,j,t} = \left(\delta_j^{EN} \frac{PE_t}{PQ_{E,t}} \right) \frac{1}{1 - \rho_j^E} E_{j,t} \quad (\text{B.23})$$

$$Y_{i,t} = A^Y \cdot \left[\delta_i^k \cdot K_{i,t}^{\rho_i^Y} + \delta_i^l \cdot L_{i,t}^{\rho_i^Y} \right] \frac{1}{\rho_i^Y} \quad (\text{B.24})$$

$$L_{j,t} = \left(A^{Y\rho_j^Y} \cdot \delta_j^l \cdot \frac{PY_{j,t}}{w_t} \right) \frac{1}{1 - \rho_j^Y} Y_{j,t} \quad (\text{B.25})$$

Trade

$$VW_{i,j,t} = \gamma_{i,j}^{VW} \cdot \left[\delta_{i,j}^{vm} VM_{i,t}^{\rho_i^A} + \delta_{i,j}^{vir} VIR_{i,t}^{\rho_i^A} \right] \frac{1}{\rho_i^A} \quad (\text{B.26})$$

$$\frac{VM_{i,j,t}}{VIR_{i,j,t}} = \left[\left(\frac{\delta_{i,j}^{vm}}{\delta_{i,j}^{vir}} \right) \cdot \left(\frac{PIR_{i,t}}{PM_{i,t}} \right) \right] \frac{1}{1 - \rho_i^A} \quad (\text{B.27})$$

$$VIR_{i,j,t} = \gamma_{i,j}^{vir} \cdot \left[\delta_{i,j}^{vi} VI_{i,t}^{\rho_i^A} + \delta_{i,j}^{vr} VR_{i,t}^{\rho_i^A} \right] \frac{1}{\rho_i^A} \quad (\text{B.28})$$

$$\frac{VR_{i,j,t}}{VI_{i,j,t}} = \left[\left(\frac{\delta_{i,j}^{vr}}{\delta_{i,j}^{vi}} \right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}} \right) \right] \frac{1}{1 - \rho_i^A} \quad (\text{B.29})$$

$$E_{i,t} = \bar{E}_i \cdot \left(\frac{PEX_{i,t}}{PQ_{i,t}} \right)^{\sigma_i^E} \quad (\text{B.30})$$

National Demand

$$R_{i,t} = \sum_j VR_{i,j,t} + \sum_h QHR_{i,h,t} + QVR_{i,t} + QGR_{i,t} \quad (\text{B.31})$$

Total absorption equation

$$X_{i,t} + M_{i,t} = \sum_j VW_{i,j,t} + \sum_h QH_{i,h,t} + QV_{i,t} + QG_{i,t} + E_{i,t} \quad (\text{B.32})$$

Households and other Domestic Institutions

$$YH_t = SHL \cdot LY_t + SHK \cdot KY_t + Trf_t \quad (\text{B.33})$$

$$C_t \cdot CPI_t = YH_t - S_t \quad (\text{B.34})$$

$$LY_t = (1 - \tau_t) L_t^S (1 - u_t) w_t + Trf_t \quad (\text{B.35})$$

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

$$S_t = mps \cdot [YH_t] \quad (\text{B.37})$$

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

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

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

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

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

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

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

Government

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

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

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

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

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

Investment demand

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

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

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

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

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

Time path of investment

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

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

Factors accumulation

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

$$K_{i,t} = KS_{i,t} \quad (\text{B.58})$$

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

Indirect taxes and subsidies

$$IBT_{i,t} = btax_i \cdot X_{i,t} \cdot PQ_{i,t} \quad (\text{B.60})$$

Total demand for import and current account

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

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

Steady state conditions

$$\delta \cdot KS_{i,T} = I_{i,T} \quad (\text{B.63})$$

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

$$KS_{i,t=1} = KS_{i,t=0} \quad (\text{B.64})$$

$$LS_{-1} = LS_{t=0} \quad (\text{B.65})$$

B.1. Glossary

$ij (i = j)$	The set of goods or industries
ins	The set of institutions
$dins (Cins)$	The set of domestic institutions
$dngins (Cdins)$	The set of non-government institutions
$h(Cdngins)$	The set of households
$en (Ci)$	The set of energy sectors {Coal, Ele, Gas and Oil}
$ne (Ci)$	The set of non-energy sectors
$ij (i = j)$	The set of goods or industries
Prices	
$PY_{i,t}$	Value added price
$PR_{i,t}$	National price
$PQ_{i,t}$	Output price
$PM_{i,t}$	Price of imported ROW commodities
$PEX_{i,t}$	ROW export price
$PIR_{i,t}$	Commodity price (national+ REU)
$PI_{i,t}$	Price of REU commodities
$PX_{i,t}$	Price of gross output
$PY_{i,t}$	Price of value added
CPI_t	Consumer price index
Pg_t	Government consumption price
pe_t	Energy price

PNE_t	Non-energy price
$rK_{i,t}$	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)
$VI_{i,j,t}$	REU intermediate inputs
$EN_{j,t}$	Intermediate energy input
$NE_{j,t}$	Intermediate non-energy input
$GEXP_{i,t}$	Aggregate government expenditure
$QG_{i,t}$	Total government expenditure by sector i
$QGR_{i,t}$	National government expenditure
$QGM_{i,t}$	Imports government expenditure
FD_t	Financial deficit
GY_t	Government income
$IBT_{i,t}$	Indirect business taxes
$QGM_{i,t}$	Government import expenditure
$C_{h,t}$	Aggregated household consumption
$QH_{i,t}$	Total households consumption in sector i
$QH_{en,t}$	Household consumption of energy
$QH_{ne,t}$	Household consumption of non-energy
$QHR_{i,t}$	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)
$QVI_{i,t}$	REU 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
YH_t	Household's income
KY_t	Income from capital
LY_t	Income from labour
S_t	Domestic non-government saving
u_t	Unemployment rate
w_t	Nominal wage
Trf_t	Households net transfer
$TRSF_{dngins}$	Transfer among $dngins$
$dnginsp, t$	
$\overline{TRC}_{dngins,t}$	Government's transfer to $dngins$
$IBT_{i,t}$	Indirect business taxes
$HTAX_t$	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	$\delta_i^{vir, vm, vr, vi}$	Shares parameters in CES function for intermediate goods
ρ_i^Y	Elasticity parameter between capital and labour	$\delta_i^{qvir, qvm, qvr, qvi}$	Shares parameters in CES function for investment goods
ρ_i^A	In Armington function	$\delta_{E_i}^{co, cl}$	Shares parameters in CES function for households consumption
σ_i^x	Of export with respect to term of trade	$\delta_{E_i}^{hm}$	Shares parameters in CES function for households consumption
σ_i^e	Substitution between energy and non-energy in Household consumption	$\delta_{E_i}^{gm}$	Shares parameters in CES function for government consumption
σ_i^c	Substitution elasticity between CO and EG in Household consumption	$\gamma_i^{v, vir}$	Shift parameter in CES functions for intermediate goods
σ_i^p	Substitution elasticity between Coal and Oil in Household consumption	γ_i^g	Shift parameter in CES function for households consumption goods
		γ_i^g	Shift parameter in CES function for government consumption
Parameters		$btax_i$	Rate of business tax
A_i	Factor productivity parameter in gross output function	$KM_{i,j}$	Physical capital matrix
ψ	Proportionate change in energy productivity parameter	mps	Rate of saving in institutions <i>dn</i> gins
A_{NE}^Y	Non-energy productivity parameter	τ	Rate of income tax
A^Y	Productivity parameter in value added function	δ	Rate of depreciation
$a_{i,j}^V$	Input-output coefficients for <i>i</i> used in <i>j</i>	v	Adjustment parameter in investment function
a_j^V	Share of value added on production	λ	Adjustment parameter in energy price function
$\delta_j^{Y,V}$	Shares in CES output function in sector <i>j</i>	H_{en}	Share of household energy consumption
$\delta_j^{K,I}$	Shares in value added function in sector <i>j</i>	H_{ne}	Share of household non-energy consumption

Appendix C

