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Can the composition of energy use in an expanding economy be altered by consumers' responses to technological change?

by

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Abstract:

Technological change is necessary for economies to grow and develop. This paper investigates how this technological change could be directed in order to simultaneously reduce carbon-intensive energy use and deliver a range of economic benefits. Using both partial and general equilibrium modelling we consider improvements in the efficiency in the delivery of electricity as an increasingly low carbon option in the UK. We demonstrate how linking this to policy action to assist and encourage households to substitute away from more carbon-intensive gas- to electricity-powered heating systems may change the composition of energy use, and implied emissions intensity, but not the level of the resulting economic expansion.

Keywords:

Technological change; CGE models; multiple benefits; rebound

1. Introduction

Historically, improvements in energy efficiency have been promoted as cost-effective and efficient ways to reduce energy demand and greenhouse gas emissions (European Commission, 2011; IEA, 2015; UNEP, 2014). Such efficiency increases hold out the prospect of expanding economic activity whilst simultaneously reducing energy use.[1] However, the substitution and income effects that accompany energy efficiency improvements generate rebound and possibly even backfire, which is thought to undermine the role of energy saving in environmental policy (see Revkin, 2014). In this paper we investigate whether the very forces that produce rebound can be channelled more effectively to meet environmental goals.

The International Energy Agency (2014) has emphasised the possible multiple benefits of improved energy efficiency. Technological change allows us to 'make more using less'; that is, to increase output without a corresponding rise in inputs. This expansion is typically regarded as desirable. For instance, the core focus of the UK Government's industrial strategy is productivity and emphasises the need for the UK to "embrace and benefit from the opportunity of technological change" (DBEIS, 2017, p. 12). But to a certain extent positive rebound effects reflect the expansionary impact on economic activity that accompany improvements in energy efficiency so that rebound is intimately linked to other central economic policy objectives. In this regard, it could be argued that the literature has been too limited in not recognising the positive benefits linked to rebound effects (for reviews see Gillingham et al., 2016; Greening et al., 2000; Sorrell et al., 2009). Here, we extend the

[1] We use the term expansion, and in particular economic expansion, to mean an increase in aggregate economic activity. This would typically imply increases in aggregate variables such as GDP, employment, household income and investment.

analysis to consider how rebound and macroeconomic benefits are linked, but also that the rebound process might possibly be further redirected so as to favour emissions' reduction.

The present paper uses partial equilibrium analysis and general equilibrium numerical simulation to address two inter-related research questions. The first is: can environmental policy benefit from more effectively directed energy efficiency improvements? Specifically, we consider whether the policy focus of an efficiency improvement in one type of energy (e.g. electricity) should be wider than just how that is used or extend to others (e.g. gas)? The second is: can encouraging the substitution effects associated with efficiency improvements be used to augment energy saving, without jeopardising the other multiple economic benefits of energy efficiency improvements?

We use as an illustrative example an improvement in the production of electricity which will affect the choice between electricity and gas for domestic space heating, so that a key element of rebound will reflect a shift from a more- to a less-carbon intensive fuel. This is a useful focus for the UK for two reasons. First, given that electricity in Europe tends to be highly priced per kWh relative to gas, there is a real need to improve its competitiveness as a low carbon option.[2] Second, where there are problems in the domestic uptake of energy efficiency initiatives, influencing the relative price of lower, as against higher, carbon options might be an effective way of reducing carbon emissions. In this respect, we highlight the potential for policy action to assist and encourage households in substituting in favour of electricity in heat, as against more carbon-intensive gas heating systems.[3]

[2] For example, see Eurostat analysis of electricity prices in European countries at http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics.

[3] Where electricity generation is more dependent on fossil fuel sources, gas could be a lower carbon (and more energy efficient) option (see Saunders, 2015). However, if the efficiency improvements focussed on gas, a similar analysis would apply.

The remainder of the paper is structured as follows. In Section 2, we formally model the impact of an efficiency improvement in the production of electricity on household energy demand in a partial equilibrium context. In Section 3 we present the arguments for augmenting this analysis with general equilibrium numerical simulations. In Section 4 we introduce the UK-ENVI computable general equilibrium (CGE) model. Section 5 reports the results for the base-case simulation where the efficiency improvement is introduced in a model using our default parameter values. This simulation establishes benchmark figures for changes in aggregate economic and energy use indicators. In Section 6 we undertake extensive simulation to identify the sensitivity of these impacts to changes in key household behavioural demand parameters. Conclusions are drawn in Section 7.

2. Partial Equilibrium and Domestic Heat

In this section we analyse the effect of an x% exogenous, costless, input-neutral improvement in efficiency in the production of electricity. This means that all the unit inputs are reduced by x%, so that with constant input prices domestically produced electricity similarly falls in price by x%. This would operate in a manner similar to an x% improvement in transmission efficiency; for a given generation level x% more electricity would be delivered to final consumers. Note that this is also analogous to an increase in the efficiency of electricity in all uses, if the electricity is measured in efficiency units. In the present case, if the reduction in the electricity price elicits no response in electricity use there is zero rebound; the resources used in the production of electricity will fall by x%. Rebound and backfire therefore occur where electricity use increases by less than, and greater than, x% respectively

Our specific focus in this section is the analysis in a partial equilibrium setting of the delivery and consumption of household services that provide warmth and comfort. In this context, we treat domestic space heating as a composite good made up of the consumption of electricity, *e*, and gas, *g*. The efficiency improvement in the production of electricity generates a fall in the price of electricity, whilst the prices of all other services and commodities (including gas), and household nominal income, remain constant. The price elasticity of demand for domestic space heating and the elasticity of substitution between electricity and gas are labelled as η and σ respectively. Both elasticities take positive values and the initial share of electricity in domestic space heating is *s*.

To measure the impact of this price reduction, expressions are required for the elasticity of demand for both electricity and gas with respect to a change in the price of electricity. Holden and Swales (1993) derives expressions for the price elasticity of demand for inputs in a two-factor production function and the same framework can be adapted so as to apply equally well to consumption (Figus et al., 2018; Figus and Swales, 2018). The partial equilibrium demand elasticities are given in equations (1) and (2).

(1) $$\frac{\dot{e}}{\dot{p}_e} = \sigma\,(s-1) - s\eta \leq 0$$

(2) $$\frac{\dot{g}}{\dot{p}_e} = s\,(\sigma - \eta) < 0 \;\; iff \; \sigma < \eta$$

where the dot notation represents proportionate changes. For the x% Hicks-neutral increase in the efficiency of the production of electricity: $\dot{p}_e = -x$. Substituting into equations (1) and (2), the proportionate changes in the demand for electricity and gas are:

(3) $$\dot{e} = x(\sigma(1-s) + s\eta) \geq 0$$

(4) $\dot{g} = xs(\eta - \sigma) < 0 \ iff \ \sigma > \eta$

Note from equation (3) that the demand for electricity never falls as a result of the increase in efficiency with which it is produced. In the present context, this represents the rebound effect. However, generation inputs per unit of delivered electricity have fallen, so that for the level of electricity generation to rise, then $\dot{e} > x$. This requires $\sigma(1 - s) + s\eta$, the weighted sum of the demand and substitution elasticities, to be greater than unity. In that case backfire would occur.

However, we are more interested in the demand for gas. The fall in the composite price of domestic space heating will increase the demand for both gas and electricity whilst the fall in the price of electricity relative to gas will lead, other things being equal, to a fall in the household use of gas. From equation (4) it is clear that under partial equilibrium, gas use will fall as long as the elasticity of substitution between electricity and gas, σ, is greater than the elasticity of demand for domestic space heating, η.

A central concern is the sensitivity of these results to changes in the demand elasticities, which is of particular relevance, given that σ and η are behavioural, rather than technical, parameters and could be influenced by government policy. Differentiating equations (3) and (4) with respect to η gives:

(5) $\frac{\partial \dot{e}}{\partial \eta} = \frac{\partial \dot{g}}{\partial \eta} = xs$

For both of the energy inputs to domestic heat, increasing η produces the same positive proportionate increase in the use of the energy source. Therefore making the demand for space heating more price elastic will increase the use of electricity and gas. Of course, where gas use falls as a result of the reduction in the price of electricity, the size of that reduction will be reduced by the increase in the value of η.

Expressions (6) and (7) show the results of differentiating functions (3) and (4) with respect to σ.

(6) $$\frac{\partial \dot{e}}{\partial \sigma} = x(1-s) > 0$$

(7) $$\frac{\partial \dot{g}}{\partial \sigma} = -sx < 0$$

Increasing the price sensitivity of the choice between electricity and gas again increases the rebound for electricity, as shown in expression (6), but has a negative effect on the change in the use of gas. The significance of a policy steering the rebound effect away from gas towards the less carbon intensive electricity is clear.

3. General Equilibrium

In a UK context, the increasing capacity for low carbon electricity (via renewables and nuclear generation) is taken as the desired cleaner option as against gas. The UK's Committee on Climate Change (2015) identifies a low-carbon electricity supply as the most cost-effective way to meet the need for more generation in the 2020s, given the nation's climate change commitments. The UK Government has recently launched a consultation on phasing out coal-powered electricity generation and developing 'the pathway to a low carbon future' around electricity generation (DBEIS, 2016). However, the non-ministerial government energy regulatory department, Ofgem, while emphasising progress in decarbonising the UK electricity system and in electricity-powered heat pump technologies, also recognises the challenges in realising widespread switching from gas to electric powered domestic heating systems. Ofgem (2016, p.11) notes that "most heat technology decisions are taken at an individual property level", highlighting the role of both local and national government in building public confidence and enabling switching to electric heating systems. Areas of government action include coordinating connections, setting and refining building and appliance standards, labelling of appliances, enabling planning permission and providing financial support. However, supporting domestic heat decarbonisation is set in the context of a broader set of challenges regarding the responsiveness of UK consumers to price signals and cost reduction opportunities in energy markets (gas and electricity). For example, Ofgem (2017, p. 3) report that (in 2017) "more than half of consumers are still on default tariffs, paying higher prices".

In short, UK electricity might not yet have reached its full low carbon potential but government is considering how the shift in its role may be achieved and promoted. The notion that technical change in electricity production could facilitate a shift towards a less carbon-intensive fuel, but that intervention to improve the responsiveness of particularly domestic energy users to consequent changes in the relative price of electricity for heat, is therefore of high policy relevance.

The partial equilibrium approach gives some very straightforward guidelines for analysing the impact of such an efficiency change, but imposes restrictive assumptions. This means that in order to investigate fully this particular issue a general equilibrium analysis is required. To begin, through its effect on the electricity price, the Hicks-neutral efficiency improvement in the production of electricity has an impact on all uses of electricity, including industrial, household and export demand. The potential substitution and output effects discussed in Section 2 will differ across uses. At the very least, this implies that the overall effect is the weighted sum of the individual effects.

Second, the positive impact of the efficiency change in the partial equilibrium case only operates through the reduction in the price of electricity, and therefore the price of space heating, to the consumer. However, the subsequent adjustments in the composition of consumption will have aggregate impacts in the sense that they change the pattern of production. This change in itself can have positive or negative effects on aggregate measures such as GDP or employment, depending primarily on the labour and import intensities of expanding and contracting sectors.[4]

Third, the changes in efficiency here impact the competitiveness of the economy. In so far as industries use electricity as an intermediate input, the fall in the price of electricity will reduce costs in production across all sectors. There will also be indirect cost reductions through the subsequent knock-on reduction in the prices of intermediate inputs generally and also potential impacts on the nominal wage. This increase in competitiveness has an expansionary impact in that it increases exports and reduces import intensity.

Fourth, the changes in the demand for factors of production affect wages, employment, the cost of capital and the capital stock, and this has further impacts on product prices and household incomes. Again these effects are not captured in the partial equilibrium approach.

[4] In identifying changes in the total use of electricity, the direct reduction in electricity employed as an intermediate in the production of electricity also needs to be counted.

The perspective that we wish to adopt here, with a focus on meeting household needs and the detailed nature of how services are provided, is reflected in recent CGE literature that has placed increased emphasis on the nature of the economic expansion that results from increased energy efficiency (e.g. Broberg et al., 2015; Lecca et al., 2014). It is also consistent with the IEA (2014) 'multiple benefits' perspective and the identification of energy saving/carbon reduction gains alongside a wider set of socio-economic net benefits.

In the context of increased efficiency in household energy use, the multiple benefits could include outcomes such as reduced fuel poverty that might be delivered via a combination of lower energy requirements and real income gains. This type of argument leads authors such as Gillingham et al. (2016) to stress that rebound in energy use must be set in the context of a larger set of net welfare gains. However, there is a less widely-recognised result from economy-wide studies not limited to energy efficiency (Cui et al., 2016). This is that the extent of the economic expansion resulting from technological change is not necessarily closely correlated with the magnitude of the 'rebound' effects in energy use.

4. The UK-ENVI CGE model

In Section 5 we perform simulations using UK-ENVI, a Computable General Equilibrium model for the UK. This is an updated variant of the model developed in Turner (2009), calibrated on a 2010 UK Social Accounting Matrix (SAM).[5] The SAM identifies transactions between 30 productive industries, households, the UK Government and the rest of the world (imports, exports and income transfers). [6] This section provides an overview of the key model

[5] The SAM is produced by the Fraser of Allander Institute, University of Strathclyde and can be downloaded at http://www.strath.ac.uk/business/economics/fraserofallanderinstitute/research/economicmodelling/
[6] See Table A1 in Appendix 1 for a full list of production sectors.

elements relevant for these simulations. Generally, unless explicitly stated, we follow Turner (2009) in the UK-ENVI model specification.

4.1 Consumption

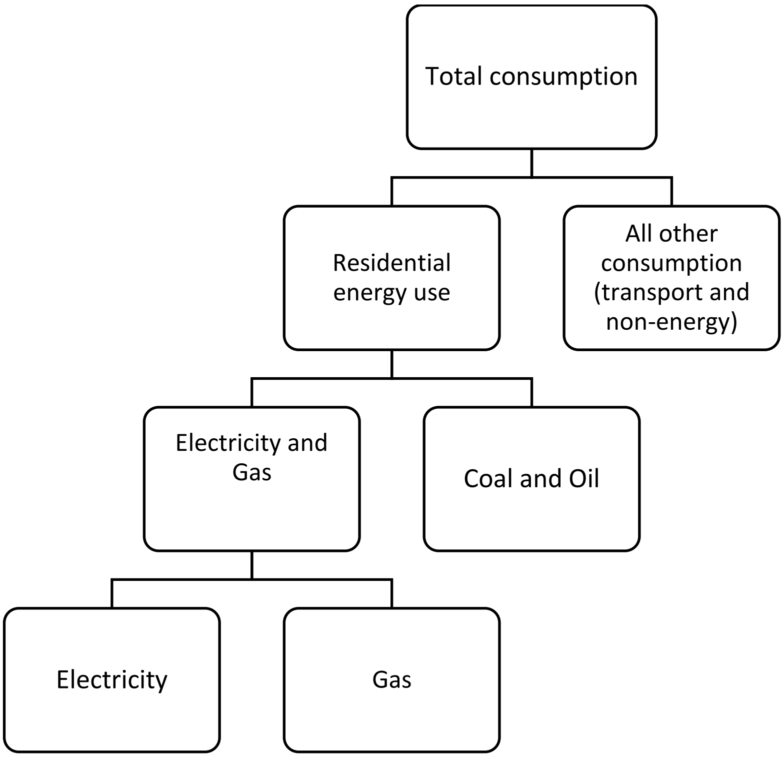
A representative household makes a decision about aggregate consumption, C, based on its current disposable income.

$$C_t = YNG_t - SAV_t - HTAX_t - CTAX_t \qquad (8)$$

In each time period, indicated by the subscript *t*, consumption is equal to gross income, *YNG*, minus savings, *SAV*, income taxes, *HTAX*, and direct taxes on consumption, *CTAX*, as shown in equation (8). Each time period is taken to be one year, given the annual reporting nature of the SAM database and the econometric studies used to determine key parameter values. In the results reported in Sections 5 and 6 we focus on long-run results. However, the simulations are run in period-by-period mode and the time path of adjustment to the long-run equilibrium can be tracked.

Figure 1 shows the nested multi-level constant elasticity of substitution (CES) function used to allocate aggregate household expenditure among different types of consumption goods and services. This is a key element of the model specification given that the work reported in this paper involves households' responses to changes in the relative prices of different goods and services in their consumption bundle.

Figure 1. The structure of consumption in UK-ENVI



In the first level, aggregate consumption is allocated between residential energy use and all other consumption. Residential energy use covers energy employed by households for heating, lighting and powering electronic appliances, etc.; all other consumption includes transport, both public and private, and all non-energy goods and services. For the substitution between residential energy use and all other consumption we apply the long-run elasticity of 0.61 estimated for use in UK-ENVI and first applied in that context by Lecca et al. (2014).[7]

In the second level, the residential energy use divides between the composites electricity-gas and coal-oil, while transport and non-energy goods combine in a separate nest. We assume a low but positive elasticity of substitution of 0.2 throughout this latter nest so that it is effectively a multi-sector single CES function. Within the residential energy nest, we assume

[7] However, we note that this estimate strictly applies for the substitutability between all household energy use (i.e. including fuel use in private transportation) and non-energy consumption.

that the value of 0.2 applies to the combination of electricity-gas and coal-oil. In the third level, electricity and gas combine with a default elasticity of 0.5. However, we subject these demand parameters to extensive sensitivity analysis in Section 6.

Though not shown in Figure 1, household consumption of each type of good/service also comprises a choice between those produced in the UK and imported alternatives produced in the rest of the world (ROW). Following Turner (2009), these are taken to be imperfect substitutes with assumed Armington elasticities in each case of 2.0.[8]

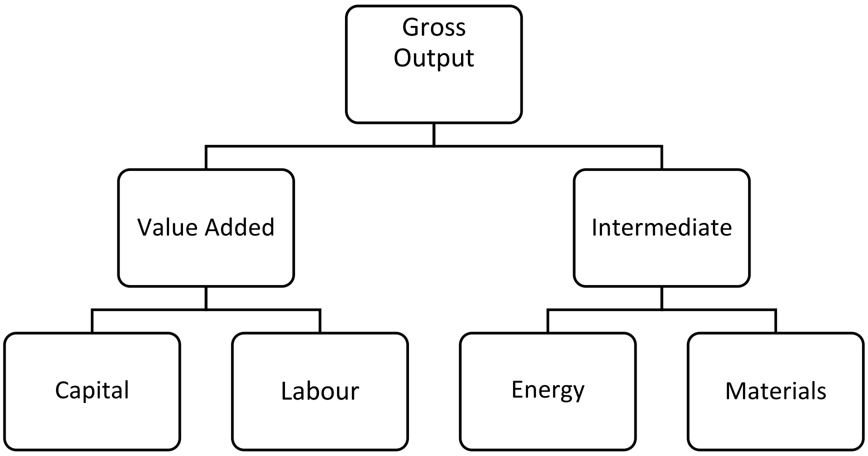
4.2 Production and investment

The production structure, outlined in Figure 2, is represented by a KLEM CES function in each of the 30 UK production sectors. Here capital (K) and labour (L) combine to form value added, while energy (E) and materials (M) form a composite of intermediate inputs. In turn, the combination of intermediate and value added gives total output. This structure is the same as that imposed by Turner (2009) and motivated by capital and labour being the sole elements of value-added (GDP). While it is not shown in Figure 2, we also follow the previous studies by assuming that within the energy composite, producers can substitute between electricity and non-electricity inputs, with the latter composed of coal, gas and oil products. [9]

[8] Turner (2009) conducts extensive sensitivity analysis around the values of Armington import elasticities and the price elasticity of export demand. Her results demonstrate that increasing these tends to deliver a bigger potential stimulus to GDP. Experiments here deliver consistent results but with limited additional insight or impact on the outcomes of the specific scenarios considered in this paper.

[9] Turner (2009) introduces more complexity and detail by disaggregating electricity generation into renewable and non-renewable sources and imposing differing elasticities within the energy nests.

Figure 2. The structure of production in UK-ENVI



Our base case scenario imposes the value of 0.3 at each nest effectively creating a single level CES production function (Turner, 2009). This is informed by early econometric work for the UK by Harris (1989). However, we augment the previous specification of UK-ENVI by assuming that imported and locally produced intermediate inputs are imperfect substitutes at the level of individual goods/services rather than for the intermediates composite as a whole (Armington, 1969). In particular, this allows domestically produced and imported energy types to combine before interacting with any other goods and services. But, in the absence of data to inform the import elasticities, we revert to the assumption of a value of 2.0 and expose this to sensitivity analysis in Section6. The same value is also assumed for the price elasticity of export demand for the output of each UK industry but again subjected to sensitivity analysis (Gibson, 1990).

Investment comprises a partial adjustment mechanism where in each period gross investment is equal to depreciation plus a fixed proportion of the gap between the desired and actual capital stock (Jorgenson, 1963). The desired capital stock in each time period and sector is the cost minimising capital stock given the industry output, wage and the replacement cost of capital. In long-run (steady-state) equilibrium, the desired and actual capital stocks are equal, and therefore at that point in each sector gross investment just covers depreciation.

4.3. Labour market and government closures

For the UK, we adopt the conventional national economy assumption that the total labour force is fixed. The real wage is negatively related to the rate of unemployment which can be motivated by efficiency wage or bargaining considerations. This formulation of the wage curve has wide empirical support for both national and regional economics (Blanchflower and Oswald, 1989).[10]

$$\ln\left[\frac{w_t}{cpi_t}\right] = \varphi - \epsilon \ln(u_t) \qquad (9)$$

In Equation (9) w is nominal wage, cpi is the consumer price index, φ is a parameter calibrated to the steady state, ϵ is the elasticity of the real wage with respect to the level of unemployment, u, and, in the absence of more recent estimates for the UK, it is assumed to take a value of 0.064 (Layard et al., 1991).

Regarding the government closure, for simplicity we assume that government expenditure is fixed in nominal terms. Any variation in tax revenues driven by changes in economic activity is absorbed by adjusting the Government's deficit. This is broadly consistent with the current UK Government's approach to addressing the public deficit.[11]

[10] With a fixed labour force, the unemployment rate is 1 minus the employment rare. The wage curve is therefore observationally equivalent to a standard full employment labour supply function, where the employment rate is positively related to the real consumption wage. In such an interpretation unemployed workers are treated as voluntarily consuming leisure.

[11] See the UK Government's 2017 (spring) budget statement at https://www.gov.uk/government/publications/spring-budget-2017-documents/spring-budget-2017.

5. Base case scenario

In this section the UK-ENVI CGE model is used to simulate a 5% permanent step increase in efficiency in all inputs in the UK electricity sector. The exogenous efficiency improvement is introduced in period 1 and the model is then run forward until long-run equilibrium is achieved. We focus here almost solely on the long-run values, where the capital stock in all production sectors is fully adjusted to the efficiency improvement. Essentially we simulate the impact of the single efficiency shock in order to isolate the system-wide effects of that shock. As noted in Section 3.3, an important feature of the simulations is that even into the long run, the labour force is assumed to be fixed, although there is some flexibility in labour supply through endogenous variations in the employment rate.

Table 1 reports the results from this base-case scenario which uses default parameter values. All figures for an extensive set of aggregate endogenous economic variables are shown as the percentage changes from their initial values. These data are important for understanding the economic impact of efficiency improvement and provide important information for an evaluation of the multiple benefits. This said, the main focus of the paper remains the effect on energy use and information is presented for electricity and gas use, broken down by household and industry. Nevertheless, we do not report the impact on carbon emissions. This is because the base year data still include relatively high levels of coal generation and much progress has been made subsequently with the recent closures of coal-fired power stations.

The key to the aggregate results lies in the 0.22% and 0.24% falls in, respectively, the CPI and replacement cost of capital which underpin the productivity-led economic expansion. This induces increased export demand which stimulates economic activity, employment and the real and nominal wage. These changes in factor prices produce the substitution of capital for labour which, together with the increase in output, stimulates investment. There is a simultaneous expansion in household consumption. Therefore in the long run we observe a relatively balanced growth of 0.36%, 0.34% and 0.34% in investment, exports and household consumption.

Table 1. The long-run impacts of a 5% increase in total factor productivity in the UK electricity supply industry (percentage changes from initial values, base case scenario)

GDP	0.32
CPI	-0.22
Investment	0.36
Exports	0.34
Household consumption	0.34
Replacement cost of capital	-0.24
Nominal wage	0.14
Real wage	0.35
Employment	0.22
Unemployment rate	-3.48
Energy (consumer) price	-1.80
Electricity (consumer) price	-3.65
Gas (consumer) price	-0.01
Total energy use	0.37
Total electricity use	0.96
Total gas use	-0.12
Energy gross output	1.19
Electricity gross output	2.81
Gas gross output	-0.14
Industry energy use	-0.03
Industry electricity use	0.40
Industry gas use	-0.54
Household energy use	1.44
Household electricity use	2.37
Household gas use	0.49

This is associated with an overall increase in GDP and employment of 0.32% and 0.22% with the latter coming through a 3.48% reduction in the level of unemployment. 90% of the GDP expansion is achieved within 5 years and over 99% of it in 10 years. This implies that, depending on the timing of implementation, the full impacts of the technological change would almost entirely occur within the timeframe of the UK's 2030 carbon budget targets so that policy actions and outcomes may be considered in this context.

In the long run, the relative energy prices facing the consumer substantially change. There is a very small, 0.01%, reduction in the gas price, which is less than the fall in CPI, but a 3.65% decline in the electricity consumer price.[12] Total energy use increases by 0.37%, which includes an increase in total electricity use of 0.96 % and a fall in the use of gas by 0.12%. The increase in the use of electricity is not surprising, given the fall in its price. Given that a key aspect of the simulations is to test whether the replacement of gas by electricity through technological change is a viable policy, this result is encouraging. However, it is instructive to compare the changes in industrial and household energy use.

In industry, there is a fall in energy use of 0.03%; electricity use increases by 0.40% but gas use falls by 0.54%. The changes in industrial use reflect the complex interaction of efficiency, substitution and output effects. In the base year data both electricity and gas are important inputs in electricity production, so that the input-neutral increase in efficiency in that sector will, ceteris paribus, reduce their use. However, the increase in GDP boosts industrial demand and this is reinforced for electricity by the fall in its price. The decline in

[12] The consumer prices are made up of the price of domestically produced commodities and imports, where the prices of the latter are held constant in the UK-ENVI simulations.

gas use is mainly due to its reduced employment in thermal electricity generation resulting from the efficiency improvement.[13]

However, the primary focus in this paper is household energy use and here the base case outcome is less reassuring in the policy context of achieving low carbon economic expansion. Table 1 shows total energy use in the household sector increasing by 1.44%. This comprises a 2.37% and 0.49% increase in the use of electricity and gas respectively. This result is particularly problematic, though not unexpected, for gas. Recall that in the partial equilibrium analysis in Section 2, the demand for gas will rise when the price of electricity falls if the elasticity of demand for space heating is greater than the elasticity of substitution between gas and electricity. In this case the elasticity of demand for the energy composite is 0.61 whilst the elasticity of substitution between gas and electricity is 0.5.

There are obvious differences, as identified in Section 3, between the partial and general equilibrium approaches. In particular, in partial equilibrium household income is held constant, whereas in the general equilibrium simulation, primarily as a result of the increased competitiveness produced by the fall in electricity price, total household consumption increases by 0.34%, enabled by a real income boost. Moreover, in general equilibrium, the price ratio between electricity and gas is 3.64%, rather than the 5% which would be imposed in a naïve partial equilibrium approach. The price change clearly reflects more than the direct impact of the efficiency change in electricity production; there is the impact of imports of gas and electricity, as well as changes in the price of inputs, including labour. Finally, the

[13] As noted in Section 1, the electricity supply chain activity reflects the generation mix reported in the 2010 database. This has already begun to change with the very recent closure of coal-fired power plants and will continue to change if the UK Government plans outlined in DBEIS (2016) are realised.

demand system imposed in the CGE simulations, as shown in Figure 1, whilst not identical to that used in Section 2 is qualitatively very close.

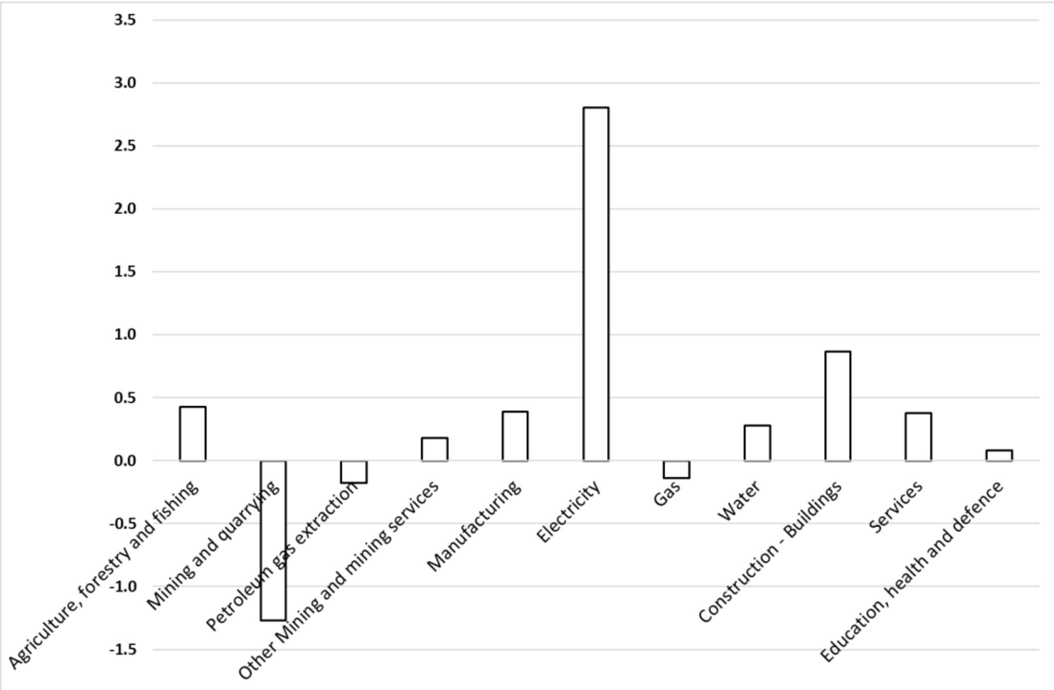
Therefore whilst the results qualitatively reflect the demand and substitution effects identified in the partial equilibrium analysis, the detailed figures indicate the importance of taking a wider perspective. The impacts of the various factors not included in the partial equilibrium analysis are not unidirectional, so that the net effect is difficult to identify a priori. Using equations (3) and (4), the partial equilibrium results for the change in household consumption of electricity and gas would be 2.68% and 0.37%, as against the CGE estimates of 2.37% and 0.49%. In this case, whilst partial equilibrium results are reasonably close to their general equilibrium counterparts, the change in the household use of gas is still underestimated by one third whilst the corresponding figure for electricity is overestimate by over one tenth. Also, clearly the quantification of the wider economic benefits is not available under partial equilibrium.

Figure 3 reinforces the narrative by adding some sectoral disaggregation. In this figure, for reporting purposes, the 30 sectors of the simulation model are reduced to 11.[14] With a full long-run adjustment, apart from the gas and the upstream energy supply chain sectors, all other sectors experience an expansion.[15] This reflects the boost to competitiveness as energy input costs fall with the increase in productivity in electricity supply. The biggest expansion in activity is enjoyed by the electricity sector itself, where output grows by 2.81%, with both industrial and household demand increasing, largely (but not entirely) at the expense of gas. However, all household energy use – for motive and non-motive purposes - rises into the long

[14] The aggregation is shown in Table A1.1 in Appendix 1.
[15] These upstream energy supply chain is primarily coal, gas and oil mining/extraction industries which supply inputs to both gas and electricity.

run as the overall cost of energy falls and incomes increase, with electricity being the main beneficiary.

Figure 3. Long-run impacts on UK industry outputs of a 5% increase in all-input productivity in the UK electricity supply industry (percentage from initial values, base case scenario)



From a multiple benefits perspective, the general increase in efficiency in the delivery of electricity is an effective policy. There is a reduction in supply-chain energy use together with a significant stimulus to economic activity. However, using the default parameter values of the base case scenario, the attempt to decarbonise domestic heat is not supported. In order to fulfil this role, the household substitution elasticities between electricity and gas need to be increased. Given that these are behavioural parameters, they are likely to be amenable to change through government policy, for example through the range of actions identified by Ofgem (2016) to affect property level decisions to switch to, for example, electric heat pump systems. These were highlighted in Section 3 and focus on building public confidence and switching through coordinating connections, building and appliance standards, labelling, planning permission and financial support.

In the next section, we test the sensitivity of the base case scenario results to changes in the household demand elasticities that might be affected by policy initiatives and actions in these areas. In particular, we wish to test whether it is possible to reduce household gas consumption without jeopardising other aspects of the multiple benefits of the energy efficiency improvement.

6. Sensitivity to key behavioural parameters

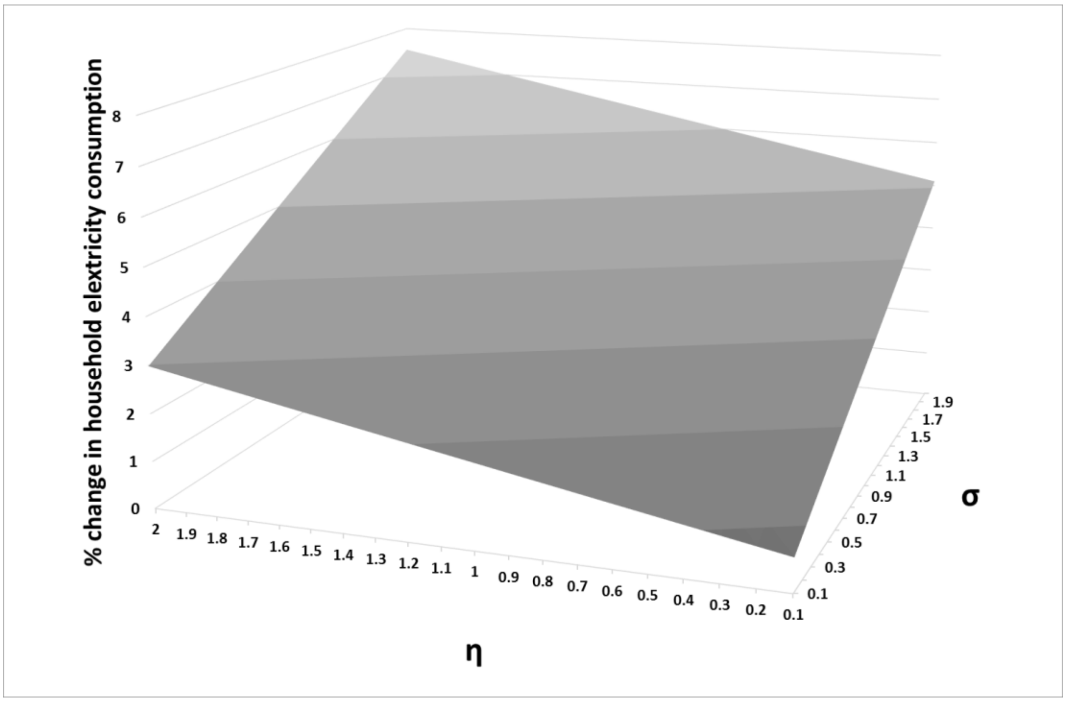
The results in Section 5 provide a benchmark. However, the primary aim of the paper is to measure the impact on household electricity and gas use of varying the responsiveness of consumers to changes in energy prices. In this section we therefore report the sensitivity of the simulation results for changes in energy use reported in Table 1 to systematically varying key parameter values. The parameters in which we are particularly interested are the behavioural household demand elasticities identified in the partial equilibrium analysis shown in Section 2. Results are shown in Figures 4 and 5.[16]

The nesting of these household demand composites was shown in Figure 1. The relevant three elasticities are those between electricity and gas, between the electricity-gas and coal-oil composites, and between residential energy use and all other consumption composites. In

[16] We do not complicate the sensitivity experiment by including variation in production, as well as consumption, substitution possibilities. Government policy typically assumes that firms are responsive where making a given change in their own commercial interest. However, clearly increasing firms' sensitivity to variation in energy prices would reinforce the changes occurring in consumption.

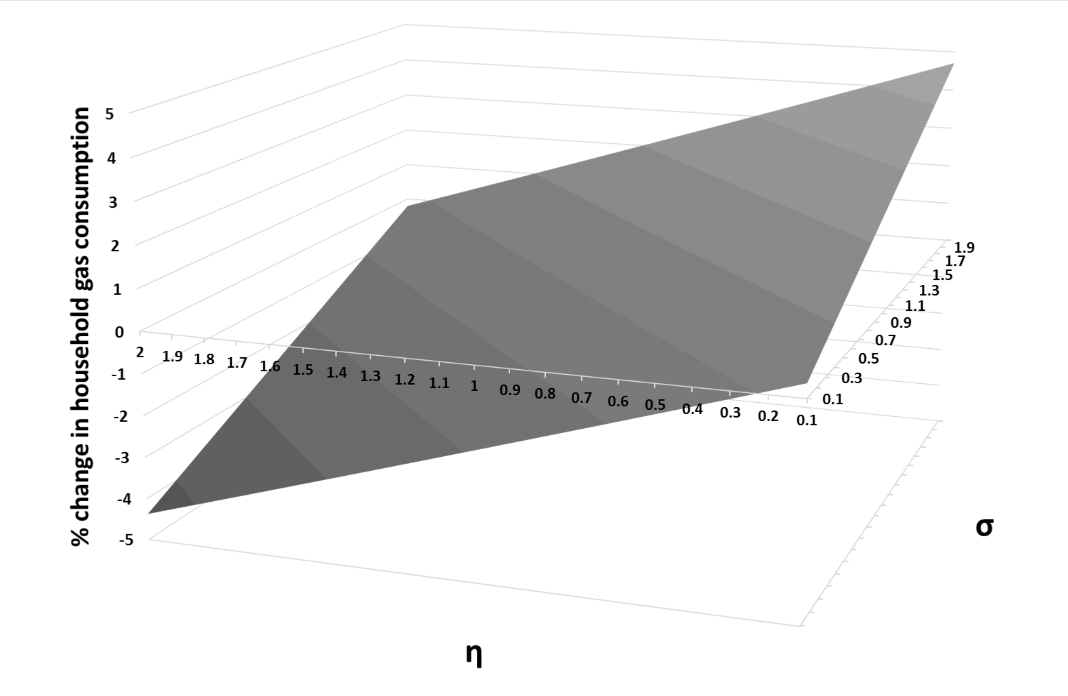
each case we test for sensitivity by varying the elasticity values between 0.1 and 2.0 by 0.1 at a time. Trials revealed that the simulation results were almost wholly insensitive to changes in the elasticity of substitution between the electricity-gas and coal-oil composites. Varying this elasticity over the full range brought extremely small changes in GDP and household electricity and gas use.[17] We therefore concentrate on the elasticities between electricity and gas, and between residential energy use and all other consumption composites. These are the substitution elasticities in the nests at the bottom and top of the household energy consumption tree. They correspond broadly to the parameters σ and η in the partial equilibrium analysis and we will use these labels as shorthand here.

Figure 4. Percentage change from the initial period values in household electricity consumption for variations in the household demand elasticities σ and η.



[17] Varying the elasticity of substitution between the electricity-gas and coal-oil composites between 0.1 and 2.0 never changed the energy or GDP figure by more than 0.01%.

Figure 5. Percentage change from the initial period values in household gas consumption for variations in the household demand elasticities σ and η.



Figures 4 and 5 report the simulation values of the percentage changes in household electricity and gas use for combinations of these household demand elasticities. In both cases the change in the household fuel use is given on the vertical axis whilst the values of the σ and η parameters are represented on the horizontal plane. Qualitatively, the results are prefigured in the partial equilibrium analysis of Section 2. In Figure 4, the increase in household electricity use is always positive, independent of the parameter values, and the size of the change is positively related to each of the elasticities, σ and η.

However, again, our primary focus is the impact on gas consumption. Figure 5 shows that improving the efficiency of the production of electricity can have a positive or negative impact on household gas consumption, depending on parameter values. In this case, household gas consumption is increasing in η, and decreasing in σ. Moreover, the division between the positive and negative changes gas use occurs approximately where the value of

σ is equal to the value of η. For example, where $\eta = 0.2$, gas consumption falls only for values of σ above 0.3. However, if $\eta = 1.7$, gas consumption falls where σ is above 1.

As was reported in Table 1, with the default values for σ and η (0.5 and 0.61), household gas use increases by 0.49%. However, even a small increase in σ to 0.7 is enough to reduce household consumption of gas. Where policy actions aim to support decarbonisation of household heat through increased efficiency in the production of electricity, they will be most effective for high values of the substitution between electricity and gas and for low values for residential energy use as a whole. Such elasticity adjustments could be achieved in the first case through policy initiative such as to support switching to electric heating systems (Ofgem, 2016), and in the second case through promotion of wider energy conservation/reduction in the household sector. For example, the reduction in household gas use is greatest, at -4.37%, where $\sigma = 2.0$ and $\eta = 0.1$. With these parameter values, the increase in household electricity use (and therefore the implicit rebound) is greater than for the base-case scenario reported in Table 1. However, given that this high increase in electricity use reflects substitution away from gas, under these circumstances improvements in the production of decarbonised electricity would be a very effective policy.

One concern is whether attempting to increase the household price sensitivity between electricity and gas will affect other multiple benefits of the efficiency improvements. Taking GDP as the best single indicator of such benefits, for the sensitivity simulations reported in Figures 4 and 5 we have also calculated variations in the change in GDP (see Table A2.1 in Appendix A2). However, these changes are extremely small for the variations in the household demand parameters within this range. With the default elasticities, as shown in Table 1 there is a 0.32% increase in UK GDP as a result of the 5% increase in efficiency in the production of electricity. This is an absolute increase of £4,169 million. When σ is increased there is a very slight fall in GDP impact but even where σ is varied across the whole range between 0.1 and 2.0, the change in GDP only differs by £5 million.[18]

This insensitivity of GDP to changes in σ is also characteristic of other aggregate economic variables and prices shown in Table 1. This includes total household energy use. Their sensitivity to variations in σ are shown in Table A2.2 in Appendix 2. That the percentage point differences across substitution elasticities in the household consumption function are extremely small reflects the core conjecture of the paper that the greatest impact of policy action to support and encourage a shift to low carbon heating systems is on the use of electricity and gas, and not on the wider economic benefits generated. Thus, attempts to reduce the household use of gas by greater substitution of electricity are clearly not significantly restricted by any negative impacts on the other multiple benefits of the efficiency improvement.[19]

7. Conclusions and directions for future research

A great deal of research and policy attention has focused on direct, indirect and economy-wide rebound effects associated with economic responses to increased efficiency in the use of energy. More recently, the literature has suggested that such effects are symptomatic of a range of 'multiple benefits' associated with economic expansion triggered by increased energy efficiency and that the rebound debate must be set in the context of a considering a wider set of net welfare gains (IEA, 2014).

[18] In comparison, the absolute changes in household gas and electricity use across these elasticity variations are £517 million and £548 million respectively. Given that these have opposite signs, total household energy use changes by £31 million.

[19] Table A2.1 in Appendix 2 shows the absolute change in GDP using the same demand elasticity grid.

In this paper we argue that energy efficiency (and associated 'rebound' in energy use) should be viewed in the wider context of the technological change that is necessary for economies to grow and develop. We extend to propose that the endogenous economic adjustments that accompany an improvement in energy efficiency, of which rebound is one, should be thought of as an opportunity to further influence energy saving. That is to say, we focus on the key challenge of directing technological change and influencing reactions so as to simultaneously deliver the wider societal benefits of economic expansion in a manner that reduces damaging environmental impacts.

We use partial equilibrium and an illustrative CGE simulation exercise to consider the economic and energy use response to increased input-neutral technological progress in the delivery of a low carbon energy option. We focus on the case of improved efficiency in the network supply of (relatively) low carbon electricity as an alternative to gas in running domestic heating systems in the UK. We direct attention to the impact on the level and composition of household spending and overall GDP if households become more responsive to the improved relative competitiveness of that electricity. Our results suggest that improving the price responsiveness of households to more efficient electricity supply permits reduced domestic reliance on gas without affecting the macroeconomic benefits realised.

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Appendix 1

Table A1.1: Production sectors in the UK- ENVI model, corresponding sectors in the 2010 UK IO tables, Standard Industrial Classification (SIC) codes.

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

Appendix 2.

Table A2.1. Sensitivity of GDP to changes in η and σ from a 5% Hicks-neutral technical progress in electricity production (value change from baseli

H / σ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.1	1.2	1.3	1.4
2	4137.9	4143.4	4148.9	4154.5	4160.0	4165.5	4171.0	4176.6	4182.1	4193.1	4198.7	4204.2	4209.7
1.9	4138.0	4143.6	4149.1	4154.6	4160.2	4165.7	4171.2	4176.7	4182.3	4193.3	4198.8	4204.4	4209.9
1.8	4138.2	4143.7	4149.3	4154.8	4160.3	4165.8	4171.4	4176.9	4182.4	4193.5	4199.0	4204.5	4210.1
1.7	4138.4	4143.9	4149.4	4155.0	4160.5	4166.0	4171.6	4177.1	4182.6	4193.7	4199.2	4204.7	4210.2
1.6	4138.6	4144.1	4149.6	4155.2	4160.7	4166.2	4171.7	4177.3	4182.8	4193.9	4199.4	4204.9	4210.4
1.5	4138.8	4144.3	4149.8	4155.4	4160.9	4166.4	4171.9	4177.5	4183.0	4194.1	4199.6	4205.1	4210.6
1.4	4139.0	4144.5	4150.0	4155.6	4161.1	4166.6	4172.2	4177.7	4183.2	4194.3	4199.8	4205.3	4210.9
1.3	4139.2	4144.7	4150.3	4155.8	4161.3	4166.9	4172.4	4177.9	4183.4	4194.5	4200.0	4205.6	4211.1
1.2	4139.4	4145.0	4150.5	4156.0	4161.6	4167.1	4172.6	4178.1	4183.7	4194.7	4200.3	4205.8	4211.3
1.1	4139.7	4145.2	4150.7	4156.3	4161.8	4167.3	4172.9	4178.4	4183.9	4195.0	4200.5	4206.0	4211.6
0.9	4140.2	4145.7	4151.2	4156.8	4162.3	4167.8	4173.4	4178.9	4184.4	4195.5	4201.0	4206.6	4212.1
0.8	4140.4	4146.0	4151.5	4157.0	4162.6	4168.1	4173.6	4179.2	4184.7	4195.8	4201.3	4206.8	4212.4
0.7	4140.7	4146.3	4151.8	4157.3	4162.9	4168.4	4173.9	4179.5	4185.0	4196.1	4201.6	4207.1	4212.7
0.6	4141.0	4146.6	4152.1	4157.6	4163.2	4168.7	4174.2	4179.8	4185.3	4196.4	4201.9	4207.4	4213.0
0.5	4141.3	4146.9	4152.4	4157.9	4163.5	4169.0	4174.5	4180.1	4185.6	4196.7	4202.2	4207.7	4213.3
0.4	4141.6	4147.2	4152.7	4158.2	4163.8	4169.3	4174.9	4180.4	4185.9	4197.0	4202.5	4208.1	4213.6
0.3	4142.0	4147.5	4153.0	4158.6	4164.1	4169.6	4175.2	4180.7	4186.3	4197.3	4202.9	4208.4	4213.9
0.2	4142.3	4147.8	4153.4	4158.9	4164.4	4170.0	4175.5	4181.1	4186.6	4197.7	4203.2	4208.7	4214.3
0.1	4142.6	4148.2	4153.7	4159.3	4164.8	4170.3	4175.9	4181.4	4187.0	4198.0	4203.6	4209.1	4214.6

Table A2.2. Percentage point changes from baseline elasticity value of 0.5.

	elasticity between electricity and gas σ					
	0.1	0.3	0.7	0.9	1.1	1.3
GDP	0.00	0.00	0.00	0.00	0.00	0.00
CPI	0.00	0.00	0.00	0.00	0.00	0.00
Investment	0.00	0.00	0.00	0.00	0.00	0.00
Exports	0.00	0.00	0.00	0.00	0.00	0.00
Household consumption	0.00	0.00	0.00	0.00	0.00	0.00
Replacement cost of capital	0.00	0.00	0.00	0.00	0.00	0.00
Nominal wage	0.00	0.00	0.00	0.00	0.00	0.00
Real wage	0.00	0.00	0.00	0.00	0.00	0.00
Employment	0.00	0.00	0.00	0.00	0.00	0.00
Unemployment rate	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00
Energy price	0.00	0.00	0.00	0.00	0.00	0.00
Electricity price	0.00	0.00	0.00	0.00	0.00	0.00
Gas price	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00
Energy gross output	-0.02	-0.01	0.01	0.02	0.03	0.04
Electricity gross output	-0.19	-0.09	0.09	0.19	0.28	0.37
Gas gross output	0.45	0.22	-0.22	-0.44	-0.66	-0.88
	0.00	0.00	0.00	0.00	0.00	0.00
Industry energy use	-0.02	-0.01	0.01	0.02	0.03	0.04
Industry electricity use	-0.05	-0.03	0.03	0.05	0.08	0.10
Industry gas use	0.00	0.00	0.00	0.00	0.01	0.01
	0.00	0.00	0.00	0.00	0.00	0.00
Household energy use	-0.01	0.00	0.01	0.01	0.02	0.03
Household electricity use	-0.48	-0.24	0.24	0.48	0.73	0.97
Household gas use	1.02	0.51	-0.51	-1.01	-1.51	-2.01