Rebound effects for household energy services in the UK

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Abstract

This study estimates the combined direct and indirect rebound effects from energy efficiency improvements in the delivery of household energy services in the UK. Direct rebound effects relate to increased consumption of the energy service that benefits from the efficiency improvement, while indirect rebound effects relate to increased consumption of other goods and services. We estimate rebound effects in terms of GHG emissions and we only consider the 'direct' emissions associated with energy consumption - thereby ignoring the 'embodied' emissions associated with global supply chains. We use time series data from a variety of sources to estimate UK household expenditure on lighting, heating, appliances and cooking over the period 1970 to 2013, together with the consumption and price of those services. We further estimate household expenditure on transport and other goods and services over this period and use this data as inputs to a two-stage household demand model. We estimate this model using iterated seemingly unrelated regressions and use the results to derive estimates of the own-price, cross-price and expenditure elasticities for the four energy services. These estimates are then combined with data on the GHG emission intensities of each service to estimate the direct, indirect and total GHG rebound effects from energy efficiency improvements. Our results suggest *large* direct rebound effects, namely 84% lighting, 14% for heating, 63% for appliances and almost 100% for cooking. However, these effects are almost entirely cancelled out by equally large, but *negative* indirect rebound effects. As a result, the total, combined rebound effects are very small, namely 0.25% for lighting, 0.29% for heating, 3.6% for appliances and 0.7% for cooking. These surprising results derive from very large cross price elasticities between the energy services, and we are currently investigating the robustness of these estimates. We provide a number of caveats to the results, as well as indicating priorities for future research.

Keywords: *rebound effects; linear almost ideal demand system; efficiency*

1 Introduction

‘Rebound effects’ is a widely used term for a variety of economic responses to improved energy efficiency. The net result of these effects is typically to increase energy consumption and greenhouse gas (GHG) emissions relative to a counterfactual baseline in which these responses do not occur. To the extent that rebound effects are neglected in policy appraisals, the energy and emissions ‘saved’ by such measures may be less than anticipated.

Despite a growing number of studies, our knowledge of the magnitude of these rebound effects remains rather patchy. In the case of energy efficiency improvements by households, the existing evidence base has three limitations.

First, most studies of consumer rebound focus upon car travel or (to a lesser extent) household heating, since data on other energy services is harder to obtain [1,2]. Studies of lighting, for example, remain comparatively rare [3,4].

Second, most studies focus solely upon *direct* rebound effects and neglect the associated *indirect* rebound effects. For example, fuel-efficient cars may encourage increased driving (direct rebound), but the cost savings may also be spent on increased consumption of other goods and services whose provision also involves energy use and emissions (indirect rebound) [5,6]. From a global perspective, these increased emissions further reduce the environmental benefits of the energy efficiency improvement.

Third, most of the studies that do include indirect rebound focus on the *income* effects of energy efficiency improvements and neglect the associated *substitution* effects - or in other words, they use expenditure rather than price elasticities [7-9]. As a result, their estimates of rebound effects could be biased [10].

Chitnis and Sorrell [10] sought to overcome these limitations by estimating a system of equations for UK household expenditure and deriving the relevant cross price elasticities. The study suggested total rebound effects direct plus indirect) of 41% for heating, 48% for electricity services (lighting and appliances), and 78% for personal transport. However, they suggested these results could be upwardly biased, since the energy efficiency improvements were modelled as a reduction in the price of the relevant energy commodities, rather than the energy services themselves.

The present study seeks to improve upon Chitnis and Sorrell [10] by incorporating four energy services (heating, lighting, appliances and cooking) directly within the household demand model. Estimates of the consumption and price of these energy services are obtained by combining data on the price and consumption of energy commodities (broken down by end-use) with estimates of the energy efficiency of the relevant conversion equipment over the period 1970-2013.

To keep things simple, we focus upon how energy efficiency improvements may have influenced the demand for heating, lighting appliances and cooking over this period. This includes own-price effects (e.g. cheaper lighting encouraging increased lighting) and cross-price effects (e.g. cheaper lighting encouraging increased heating). The former is a direct rebound effect while the latter is an indirect rebound effect. We estimate rebound effects in terms of GHG emissions and we only consider the ‘direct’ emissions associated with energy consumption. In other words we ignore the ‘embodied’ emissions associated with the global supply chains of goods and services (e.g. those associated with extracting, processing and distributing natural gas) and hence exclude the indirect rebound effects associated with increased consumption of non-energy goods and services (e.g. furniture, food products).[1] This contrasts with Chitnis and Sorrell [10] who include these embodied emissions. However, our model can easily be extended to include embodied emissions, and can also be extended to include a more disaggregated breakdown of household expenditure.

The following section outlines the use of elasticities for estimating rebound effect, while Section 3 describes the economic model adopted and the econometric techniques employed. Section 4 summarises the data sources and highlights the trends in UK energy service consumption and prices since 1970. Section 5 presents the results, including the estimates of direct and indirect rebound effects, while Section 6 concludes.

Please note that the results reported in this paper should be treated as provisional. *Our estimates of cross price elasticities are remarkably large and we are currently investigating their robustness. We are also investigating a number of extensions to the model, including the disaggregation of transport modes. This will allow the estimation of cross price elasticities (and hence indirect rebound effects) between household energy services and transport.*

2 Defining and obtaining elasticity measures for rebound effects

Cost-effective energy efficiency improvements reduce the effective price of energy services such as heating and lighting, thereby encouraging increased consumption of those services that partly offsets the initial energy and emission savings. The marginal change in the energy (q_e) required to provide a given quantity of energy service (q_s) following a marginal change in energy efficiency ($\varepsilon = q_s / q_e$) may be expressed as:

$$\eta_{q_e,\varepsilon} = \frac{\partial \ln q_e}{\partial \ln \varepsilon} \qquad 1$$

As shown by Sorrell and Dimitropoulos [13], this may be written as:[2]

$$\eta_{q_e,\varepsilon} = -\eta_{q_s,p_s} - 1 \qquad 2$$

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[1] These ''indirect' emissions are typically estimated with the help of multiregional input output models [6,11,12]. In practice, energy commodities such as natural gas tend to provide the largest contribution to indirect rebound effects since they are more emission intensive . For example, reduced expenditure on lighting may lead to increased consumption of natural gas for heating and increased consumption of furniture products, but the (mostly direct) emissions associated with the former will typically be much larger than the embodied emissions associated with the latter.

[2] Given $q_e = q_s / \varepsilon$, $q_s = f(p_s)$ and $p_s = p_e / \varepsilon$, we have: $\eta_{q_e,\varepsilon} = \frac{\partial q_e}{\partial \varepsilon}\frac{\varepsilon}{q_e} = \frac{\varepsilon}{q_e}\left[-\frac{q_s}{\varepsilon^2} + \frac{\partial q_s}{\partial p_s}\frac{\partial p_s}{\partial \varepsilon}\right]$

Or: $\eta_{q_e,\varepsilon} = \frac{\varepsilon}{q_e}\left[-\frac{q_s}{\varepsilon^2} - \frac{1}{\varepsilon}\frac{p_e}{\varepsilon^2}\frac{\partial q_s}{\partial p_s}\right] = \frac{q_s}{\varepsilon q_e} - \frac{p_e}{\varepsilon^2 q_e}\frac{\partial q_s}{\partial p_s} = -1 - \frac{p_s}{q_s}\frac{\partial q_s}{\partial p_s}$. So: $\eta_{q_e,\varepsilon} = -\eta_{q_s,p_s} - 1$

Where η_{q_s,p_s} is the own-price elasticity of demand for the energy service (q_s) with respect to the energy cost of that service ($p_s = p_e / \varepsilon$).The negative of this elasticity is commonly taken as a measure of the *direct rebound effect* (R_D) [13]:

$$R_D = -\eta_{q_s,p_s} \qquad 3$$

If the energy service is a normal good ($\eta_{q_s,p_s} \leq 0$), the direct rebound effect will be positive ($R_D \geq 0$).For there to be no direct rebound effect, the own price elasticity of energy service consumption would need to be zero ($\eta_{q_s,p_s} = 0$). If this elasticity exceeds unity ($\eta_{q_s,p_s} < -1$), energy efficiency improvements lead to an increase in energy consumption ('backfire').

Rebound effects are commonly defined in terms of *energy consumption*, but may alternatively be expressed in terms of the associated *GHG or carbon emissions*. The GHG emissions (g_s in tCO_2e) associated with consumption of an energy service may be written as:

$$g_s = u_s^q q_s \qquad 4$$

Where u_s^q is the emissions intensity of the energy service in tCO_{2e}/unit. Aggregating over all households, we observe that individual energy services (e.g. heating) may be derived from more than one energy commodity (e.g. gas, electricity) and more than one type of conversion device (e.g. boiler, storage heater). Hence, expressed in terms of energy commodities, the GHG emissions associated with an individual energy service may be written as

$$g_s = \sum_k u_{e_k}^q \varepsilon_{e_k} q_{e_k} \qquad 5$$

Where $u_{e_k}^q$ is the emissions intensity (in tCO_{2e}/kWh) of energy commodity *k*, q_{e_k} is the consumption of that commodity (in kWh) and ε_{e_k} is the associated average conversion efficiency. The emissions intensity coefficient ($u_{e_k}^q$) may include both the *direct* emissions from combusting energy commodities and the *embodied* emissions associated with the supply chain for those commodities. We confine our attention to direct emissions in what follows, but the framework may be easily extended to include embodied emissions. Note, however, that *the magnitude of the direct rebound effect (in %) is independent of the metric used*.

Energy efficiency improvements may also change the quantity demanded of other goods and services – including other energy services. These changes may either offset or add to the energy and emission savings from the efficiency improvement, depending on whether the quantity demanded of the commodity has increased or fallen. The *indirect rebound effect* (R_{I_i}) from an individual commodity (*i*) will depend upon:

- the elasticity of demand for that commodity with respect to the price of the energy service: $\eta_{q_i,p_s} = \frac{\partial \ln q_i}{\partial \ln p_s}$; and

- the energy or emissions intensity of the commodity relative to that of the energy service: $f = \frac{u_i^q}{u_s^q}$

Where u_i^q is the energy or emission intensity of the relevant commodity. A formula for estimating the indirect rebound effect is derived in Section 3.1. Consumption of commodities that are complements (substitutes) to the energy service will increase (reduce) following the energy efficiency improvement, which in turn will increase (reduce) the indirect rebound effect. To estimate the overall indirect rebound effect, we need to sum the impacts of the energy efficiency improvement over all relevant commodities. Note that, unlike the direct rebound effect, *the magnitude of the indirect rebound effect will depend upon the metric used*.[3]

To obtain estimates of the own- and cross-price elasticities for the different energy services (η_{q_s,p_s} and η_{q_i,p_s}) we need to estimate a *household demand model* - namely, a system of *n* equations representing household demand for *n* commodities as a function of total expenditure, commodity prices and other variables - with some of these commodities being the relevant energy services (*s*). While a growing number of studies estimate own-price elasticities for individual energy services (η_{q_s,p_s}), no study has previously estimated cross-price elasticities (η_{q_i,p_s}) owing the difficulties of specifying energy services as 'commodities' within such a model [14].[4] Our study attempts to do this, with the help of an original dataset on the consumption of energy services in UK households over the period 1970 to 2013.

It is common to formulate household demand models in terms of expenditures (x_i) rather than quantity demanded (q_i) since data on expenditures is easier to obtain. It is straightforward to convert between the two using the following relationships:

$$\eta_{x_i,p_i} = 1 + \eta_{q_i,p_i} \quad (6)$$

$$\eta_{x_i,p_j} = \eta_{q_i,p_j} \quad (7)$$

$$\eta_{x_i,x} = \eta_{q_i,x} \quad (8)$$

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[3] For example, if rebound effects are measured in energy terms, a unit (kWh) of gas consumption will be equivalent to a unit of electricity consumption. But if rebound effects are measured in GHG emission terms, a unit of electricity consumption may be associated with more or less emissions that a unit of gas consumption depending upon the emission intensity of generation.

[4] Total expenditure on energy services includes the expenditure on energy commodities (e.g. unit and fixed costs for natural gas), discounted expenditure on capital equipment (e.g. boilers) and expenditure on maintaining that equipment (e.g. boiler servicing). Since the latter are difficult to isolate, expenditure on energy commodities is sometimes used as a proxy. But while this captures marginal costs, it may provide a poor estimate of total costs for some energy services (e.g. car travel)

The number of coefficients to be estimated in a household demand model can severely limit the degrees of freedom, with the result that expenditures need to be aggregated into a limited number of commodity groups. For the same reason, such models provide limited scope for including covariates and typically require restrictions to be imposed upon the parameter values to increase the degrees of freedom. A common strategy is to assume *separability* of preferences between aggregate commodity groups such as food and transport, implying that decisions on how much to spend on one group (e.g. transport) are separate from decisions on how to allocate this expenditure between the goods and services within that group (e.g. bus, car or train travel) [15].[5] This is a restrictive assumption, but it can work reasonably well if the categories are well chosen.

3 Methodology

Our approach involves estimating an econometric model to obtain own-price and cross-price elasticities for our four energy services, and using these to estimate direct and indirect rebound effects. Section 3.1 develops analytical expressions for the rebound effects, using GHG emissions as a metric and incorporating the elasticities defined in the previous section, while Section 3.2 describes the econometric model and the method of estimation.

3.1 Rebound model

Assume a household makes a costless investment that increases the energy efficiency (ε) of providing an energy service (s) by $\varsigma = \Delta\varepsilon / \varepsilon$ ($\varsigma \geq 0$), thereby reducing the energy cost (p_s) of that service by $\tau = \Delta p_s / p_s$ ($\tau \leq 0$). Let Q represent the household's baseline GHG emissions, ΔH the change in emissions that would occur *without* any behavioural responses to the lower cost energy service (the 'engineering effect'), ΔG the change in emissions that results from those behavioural responses (the 're-spending effect'), and $\Delta Q = \Delta H + \Delta G$ the net change in GHG emissions.[6] The total rebound effect (R_T) is then given by:

$$R_T = \frac{\Delta H - \Delta Q}{\Delta H} = -\frac{\Delta G}{\Delta H} \qquad 9$$

As discussed above, this is comprised of direct and indirect effects ($R_T = R_D + R_I$). I

The baseline GHG emissions for the household may be written as:

$$Q = x_s u_s^x + \sum_{i(i \neq s)} u_i^x x_i \qquad 10$$

[5] 'Weak separability' implies that the marginal rate of substitution between commodities in one group is independent of the quantities of other commodities in other groups. This allows the demand for commodities within a group to be written solely as a function of the expenditure on the group and the prices of commodities within the group, with the prices of other commodities only affecting the group expenditure and not the allocation of expenditure within the group.

[6] These variables could refer to direct emissions alone (as in this paper), or direct plus embodied emissions (as in [10]).

Where x_i is the expenditure on commodity i (in £), u_i^x is the GHG intensity of that expenditure (in tCO_{2e}/£) and x_s and u_s^x are the corresponding values of these variables for the energy service

To estimate the engineering effect (ΔH), we assume the consumption of all commodities remains unchanged while the energy cost of the energy service falls. The change in expenditure on the energy service as a consequence of the engineering effect is then given by $\Delta x_s^H = q_s \Delta p_s$. Given that $\Delta p_s = \tau p_s$ and $\Delta H = u_s^x \Delta x_s^H$ we obtain the following expression for the engineering effect:

$$\Delta H = u_s^x x_s \tau \qquad 11$$

To estimate the re-spending effect (ΔG), we must allow for the change in expenditure on each commodity group (Δx_i).The change in expenditure on the energy service itself as a consequence of the engineering effect is given by $\Delta x_s^G = p_s \Delta q_s$.[7] Adding in the change of expenditure on other commodity groups we obtain the following expression for the re-spending effect:

$$\Delta G = u_s^x \Delta x_s^G + \sum_{i(i \neq s)} u_i^x \Delta x_i \qquad 12$$

Assuming marginal changes, we can use elasticities to substitute for Δx_s^G and Δx_i in this equation:

$$\Delta G = u_s^x x_s \tau (\eta_{x_s, p_s} - 1) + \sum_{i(i \neq s)} u_i^x x_i \tau \eta_{x_i, p_s} \qquad 13$$

Substituting the expressions for ΔH (Equation 11) and ΔG (Equation 13) into Equation 9 and defining the share of commodity i in total expenditure as $w_i = x_i / x$, we arrive at the following expression for the total rebound effect:

$$R_T = (1 - \eta_{x_s, p_s}) - \sum_{i(i \neq s)} \psi_i \eta_{x_i, p_s} \qquad 14$$

Where:

[7] For the energy service itself, the total change in expenditure is the sum of the engineering and re-spending effects: $\Delta x_s = \Delta x_s^H + \Delta x_s^G$

$$\psi_i = \frac{u_i^x w_i}{u_s^x w_s} \quad (15)$$

Equations 14 and 15 are used below to estimate the rebound effect. For ease of exposition, we express elasticities in quantity form in what follows. Using Equations 6 to 8, the total rebound effect can also be expressed as:

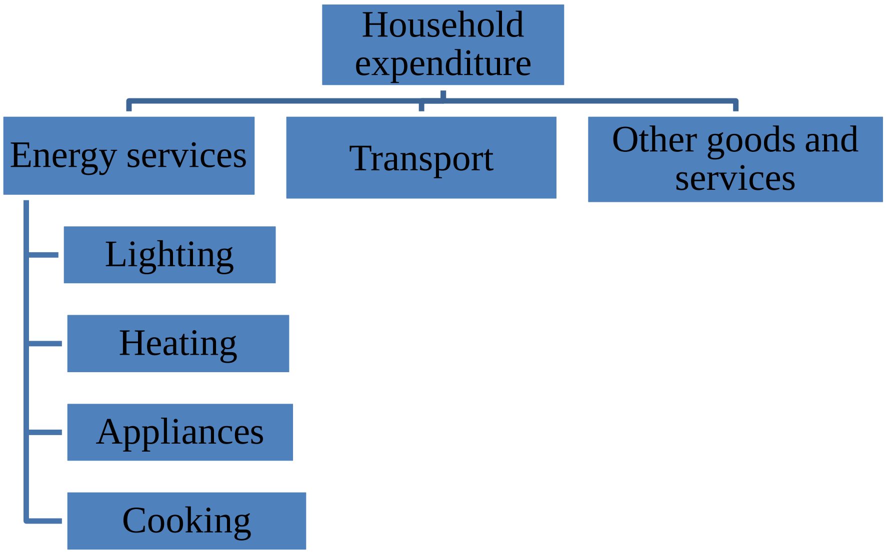
$$R_T = -\eta_{q_s,p_s} - \sum_{i(i \neq s)} \psi_i \eta_{q_i,p_s} \quad (16)$$

The first term in Equation 16 is the direct rebound effect (R_D) and the second is the indirect effect (R_I). The first depends solely upon the own-price elasticity of energy service demand (η_{q_s,p_s}), while the second depends upon the elasticity of demand for commodity *i* with respect to the energy service (η_{q_i,p_s}) and the GHG intensity and expenditure share of that commodity relative to that of the energy service (ψ_i). Hence, commodities with a small cross-price elasticity may nevertheless contribute a large indirect rebound effect if they are relatively GHG intensive and/or have a large expenditure share (and vice versa).

3.2 Econometric model

We base our household demand model on the *Linear Approximation to the Almost Ideal Demand System* (*LAIDS*). This has become the model of choice in household demand analysis since it has number of advantages over competing approaches [16]. As a compromise between resolution and degrees of freedom, we split household expenditure into three categories and assume separability to give a standard, two-stage budgeting framework (Figure 1). Households are assumed to first allocate expenditure between three aggregate groups (energy services, transport and other goods and services), and then distribute the group expenditures between sub-groups (*i*) within each group (*r*). For this study, we define four subgroups of energy services (lighting, heating, appliances and cooking), but do not disaggregate the transport or other goods and services categories. This framework allows expenditure on the energy service sub-groups to be specified as a function of the total expenditure on energy services and the prices of each individual energy service. The groups and subgroups include expenditure on both durables and nondurables.

Figure 1 Two-stage budgeting model



Let x_t^r represent the expenditure on aggregate group *r* in period *t* and w_t^r the fractional share of that group in total household expenditure (x_t):

$$w_t^r = \frac{x_t^r}{x_t} \qquad 17$$

In the first stage of the LAIDS model, this is specified as:

$$w_t^r = \alpha^r + \sum_{s=1,..4} \gamma^{rs} \ln p_t^s + \beta^r \ln(x_t / P_t) + \sum_{s=1,..3} \lambda^{rs} w_{t-1}^s + \varepsilon_t^r \qquad 18$$

Where: *r* and *s* index over the aggregate groups; p_t^s is the price of the aggregate group *s* in period *t;* x_t is total expenditure per household in that period; P_t is the Stone's price index for the aggregate groups; w_{t-1}^s is the lagged expenditure share of group *s*; α^r, γ^{rs}, β^r and λ^{rs} are the unknown parameters and ε_t^r is the error term. The Stone's price index is defined as:

$$\ln P_t = \sum_{r=1,..4} w_t^r \ln p_t^r \qquad 19$$

Our model departs from standard applications of LAIDS by including lagged expenditure shares (w_{t-1}^s) to capture the inertia in price responses - for example as a result of habit formation. The inclusion of lags also reduces problems of serial correlation [17-20]. Since the lagged expenditure shares sum to unity, we only include three in each equation to avoid multi-collinearity.[8]

[8] An alternative to dropping the lagged budget share of one commodity would be to impose the restriction: $\sum_s \lambda^{rs} = 0$. This would not affect the estimated coefficients.

We impose restrictions on the parameter values to ensure the results are compatible with consumer demand theory.[9] Specifically, *adding up* requires that expenditures on each group add up to total expenditure; *homogeneity* requires that quantity demanded remains unchanged if prices and total expenditure change by an equal proportion; and *symmetry* requires that the Slustky matrix is symmetric . These restrictions are implemented as follows:

Adding up: $\sum_r \alpha^r = 1$; $\sum_r \beta^r = 0$; $\sum_r \gamma^{rs} = 0$ *s=1,..4*; and $\sum_r \lambda^{rs} = 0$ *s=1,..3*;

Homogeneity: $\sum_r \gamma^{rs} = 0$ *s=1,..4*; Symmetry: $\gamma^{rs} = \gamma^{sr}$

The second stage of the LAIDS model distributes the group expenditures (x_t^r) between sub-groups. For the present study, this stage only applies to the energy services group. Let x_{it}^r represent expenditure on subgroup *i* in aggregate group *r* during period *t* ($i \in r$) and w_{it}^r represent the fractional share of that subgroup in the expenditure on group *r* (x_t^r):

$$w_{it}^r = \frac{x_{it}^r}{x_t^r} \qquad 20$$

This is specified as:

$$w_{it}^r = \alpha_i^r + \sum_{j=1,..k^r} \gamma_{ij}^r \ln p_{ij}^r + \beta_i^r \ln(x_t^r / P_t^r) + \sum_{j=1,..(k^r-1)} \lambda_{ij}^r w_{jt-1}^r + \varepsilon_{it}^r \qquad 21$$

Where: *i* and *j* index over the subgroups within aggregate group *r* ($i, j \in r$); k^r is the number of subgroups in aggregate group *r*; p_{it}^r is the price of subgroup *i* in aggregate group *r* in period *t;* x_t^r is expenditure on group *r* in that period; P_t^r is the Stone's price index for group *r*; α_i^r, γ_{ij}^r β_i^r and λ_{ij}^r are the unknown parameters and ε_{it}^r is the error term. The Stone's price index for group *r* is defined as:

$$\ln P_t^r = \sum_{i=1,..k^r} w_{it}^r \ln p_{it}^r \qquad 22$$

Again, the adding up, symmetry and homogeneity restrictions are imposed as follows:

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[9] Alternatively, an unrestricted model can be estimated for both the first and second stage and the homogeneity and symmetry restrictions tested. It is common for these restrictions to be rejected in empirical studies [21]. For example, the foundational LAIDS study by Deaton and Muellbauer [16] rejected these restrictions. The adding up restriction, however, is always satisfied by dropping one of the equations.

Adding up: $\sum_i \alpha_i^r = 1$; $\sum_i \beta_i^r = 0$; $\sum_i \gamma^{ij} = 0$; *j = 1,..k^r^* and $\sum_i \lambda_{ij}^r = 0$ *j = 1,.(k^r^ -1)*

Homogeneity: $\sum_i \gamma_{ij}^r = 0$ $j = 1,..k^r$ Symmetry: $\gamma_{ij}^r = \gamma_{ji}^r$

Goddard [22] derives equations for estimating the short run expenditure and price elasticities for a single stage LAIDS model[10], while Edgerton [20] derives expressions for a two-stage model. In the latter, 'total' elasticities are calculated from estimates of the 'between-group' and 'within-group' elasticities. The interpretation of these is summarised in Box 1 and the relevant formulae are summarised in Table 1 [20]. Both express the elasticities in terms of quantities rather than expenditures, using the conversions indicated in Equations 6 to 8. Here, δ_{rs} (Kronecker delta) is equal to unity when *r=s* (i.e. own-price elasticity) and zero otherwise. Similarly, δ_{ij}^r is unity when *i=j* and zero otherwise.

Box 1 Interpretation of the between-group, within-group and total elasticities

1. *Between-group* expenditure ($\eta_{q_r,x}$) and price (η_{q_r,p_s}) elasticities for the aggregate groups (*r*) respectively indicate how the quantity demanded of group *r* changes following: a) a change in total expenditure; and b) a change in the price of group *s* holding total expenditure fixed.
2. *Within-group* expenditure (η_{q_i,x_r}^r) and price (η_{q_i,p_j}^r) elasticities for each subgroup *i* within group *r* respectively indicate how the quantity demanded of this subgroup changes following: a) a change in expenditure on group *r;* and b) a change in the price of subgroup *j* within group *r* holding expenditure on group *r* fixed. Here, both *i* and *j* are within the same group.
3. *Total* expenditure ($\eta_{q_i,x}$) and price (η_{q_i,p_j}) elasticities for each subgroup *i* within group *r* respectively indicate how the quantity demanded of this subgroup changes following: a) a change in total expenditure; and b) a change in the price of subgroup *j* holding total expenditure fixed but allowing expenditure on group *r* to vary. Here, *i* and *j* may be within the same or different aggregate group.

Table 1 Analytical expressions for the between-group, within-group and total elasticities within a two-stage LAIDS model

Elasticity	**Expenditure**	**Uncompensated price**
Between-group	$\eta_{q_r,x} = 1 + \frac{\beta^r}{w^r}$	$\eta_{q_r,p_s} = \frac{\gamma^{rs} - \beta^r w_s}{w_r} - \delta_{rs}$
Within-group $(i, j \in r)$	$\eta_{q_i,x_r}^r = 1 + \frac{\beta_i^r}{w_i^r}$	$\eta_{q_i,p_j}^r = \frac{\gamma_{ij}^r - \beta_i^r w_j^r}{w_i^r} - \delta_{ij}^r$
Total	$\eta_{q_i,x} = \eta_{q_i,x_r}^r \eta_{q_r,x}$	$\eta_{q_i,p_j} = \delta_{rs}\eta_{q_i,p_j}^r + \eta_{q_i,x_r}^r(\delta_{rs} + \eta_{q_r,p_s})w_j^s$

Source: Edgerton [20],Goddard [22]

[10] Buse [23] evaluates several elasticity expressions for LAIDS model and finds these expressions are marginally the best.

The formulae in Table 1 deserve some explanation. The formula for the total expenditure elasticity for the *i*th subgroup in the *r*th group (Table 1, line 2) is simply the product of the within-group elasticity for that subgroup and the expenditure elasticity of the group.

The formula for the total price elasticity (Table 1, line 3) is more complex. Note first that when subgroups *i* and *j* are in different groups, $\delta_{rs} = 0$ and the expression reduces to:

$$\eta_{q_i,p_j} = \eta^r_{q_i,x_r} \eta_{q_r,p_s} w^s_j \qquad 23$$

Here, the first term ($\eta^r_{q_i,x_r}$) represents the change in quantity demanded of subgroup *i* following a change in expenditure on group *r;* the second term represents the change in quantity demanded of group *r* following a change in the price of group *s*; and the third term represents the share of subgroup *j* in the expenditure on group *s*. As shown by Edgerton [20], the latter is equivalent to the change in the price of group *s* following a change in the price of subgroup *j* ($w^s_j = \partial \ln p_s / \partial \ln p_j$).

When *i* and *j* are in the same group (*r*=*s*), the expression becomes:

$$\eta_{q_i,p_j} = \eta^r_{q_i,p_j} + \eta^r_{q_i,x_r}(1+\eta_{q_r,p_r})w^r_j \qquad 24$$

Here, the total cross-price elasticity equals the within-group cross-price elasticity ($\eta^r_{q_i,p_j}$), plus a product of three factors. The first of these ($\eta^r_{q_i,x_r}$) measures the change in quantity demanded of subgroup *i* following a change in expenditure on group *r;* the second measures the change in quantity demanded of group *r* following a change in the price of group *r*; and the third represents the change in the price of group *r* following a change in the price of subgroup *j* ($w^r_j = \partial \ln p_r / \partial \ln p_j$).The smaller each of these terms are, the smaller the difference between the within-group and total price elasticity.

We estimate these elasticities using the expenditure shares for the *final year* of the time series (2013). Since expenditure shares have changed significantly since 1970, the results may be sensitive to the choice made (an alternative would be to use the mean expenditure shares over the period) The total elasticities for each energy service (η_{q_s,p_s} and η_{q_i,p_s}) are used to estimate rebound effects.

4 Data

Data for the price of different commodity groups and household current expenditure on transport and other goods and services is taken from *Consumer Trends,* published by the UK Office of National Statistics (ONS). The data used for estimation are annual time series for

1970-2013. Data on total household numbers for selected years is taken from DGLC [24], with data on intermediate years estimated by linear interpolation.[11]

Data on expenditure for energy services (heating, lighting, appliance and cooking services) is compiled from a variety of sources (see Table 2), using an approach similar to that described in Fouquet [27].[12] The consumption of each energy service in each year is estimated by multiplying estimates of the energy consumption for that service by estimates of the average efficiency of the relevant conversion devices. In a similar manner, the 'price' of each energy service is estimated by dividing the unit price of the relevant energy carriers by estimates of the average efficiency of the relevant equipment. The latter represents the marginal cost of energy services, since no allowance is made for the capital cost of equipment. Since some energy services (e.g. heating) are provided by more than one energy commodity (e.g. electricity, gas), as well as by more than one conversion device (e.g. storage heaters, boilers); this process is far from straightforward. Additional challenges are created by gaps and limitations in the available data which reduces the level of confidence we can have in the results. Full details of the method employed and assumptions used are available from the authors.

Table 2 Data sources for estimating the consumption and price of household energy services

Source	**Used for**
DECC [28] Table 3.4	Residential energy consumption by end use (space heating, water heating, cooking, lighting, appliances, total)
DECC [28] Table 3.2 and 3.5 and BRE [29]	Residential energy consumption by commodity (coal, petroleum, natural gas, electricity) and end-use (space heating, water heating, cooking, lighting, appliances, total)
DECC [28] Table 3.10	Residential electricity consumption by end-use (lighting, cold, wet, consumer electronics, computing, cooking)
Cambridge Architectural Research Ltd	More disaggregated breakdown of household electricity consumption *Lighting*: incandescent, halogen, fluorescent strip, CFL, LED *Cold*: chest freezer, fridge freezer, refrigerator, upright freezer *Wet*: washing machines, washer dryers, dishwashers, tumble dryers *Consumer electronics*: TV, set-top box, DVD, games console, PSU *Computing*: desktop, laptop, monitor, printer, multifunction *Cooking*: electric oven, electric hob, microwave, kettle
DECC [30]	Residential energy consumption and expenditure by commodity
ONS [31]	Retail price index
Fouquet [27]; Wikipedia[13]	Thermal efficiency of lighting devices
Fouquet [27]; DECC [28] Table 3.34 and 3.32	Boiler efficiencies; percentage of households with hot water tanks
Fouquet [27]; BRE [29]	Thermal efficiency of UK dwellings
Brockway *et al* [32]	Thermal efficiencies of cold, wet and electronic appliances

[11] Two sets of time series data for expenditure and implied deflators (used for prices) are available: a) 1970 to 2010 consistent with the UK National Accounts for 2010 [25] and b) 1997 to 2013 consistent with the National Accounts for 2011 [26]. To create a consistent time series over the full period, we take the annual growth rates of expenditure and deflators during 1970-1997 from ONS [25] and use these to adjust the 1997 data from ONS [26].

[12] Time series have also been constructed for transport services (car, bus and rail) over this period, but these are not used here.

[13] https://en.wikipedia.org/wiki/Luminous_efficacy

Figure 2 indicates the estimated trends in energy efficiency for each energy service over this period.[14] This represents the net impact of improvements in the efficiency of individual conversion devices and changes in the mix of conversion devices use for each energy service. The efficiency of heating and cooking is estimated to have improved by ~80% since 1970, with most of the improvements in cooking efficiencies occurring since 2000. For heating, average first-law heating efficiencies were around 85% in 2013, compared to ~55% in 1970 - a change that reflects both the shift from coal to gas heating and the increasing use of gas-fired condensing boilers. The efficiency of lighting improved steadily up to 2006 and then more rapidly following the penetration of CFLs and LEDs. Average lighting efficiencies are estimated to be ~40 lumens per watt (lh/W) in 2013 compared to ~18 lm/W in 1970. Trends in appliance efficiencies are strongly influenced by the improvements in wet and cold appliance efficiencies since 2000, together with the rapid growth in electronics and computing. Overall, average appliance efficiencies are estimated to have increased by ~400% over this period.

Figure 2 Average efficiency of UK household energy services provision 1970-2013 (index)

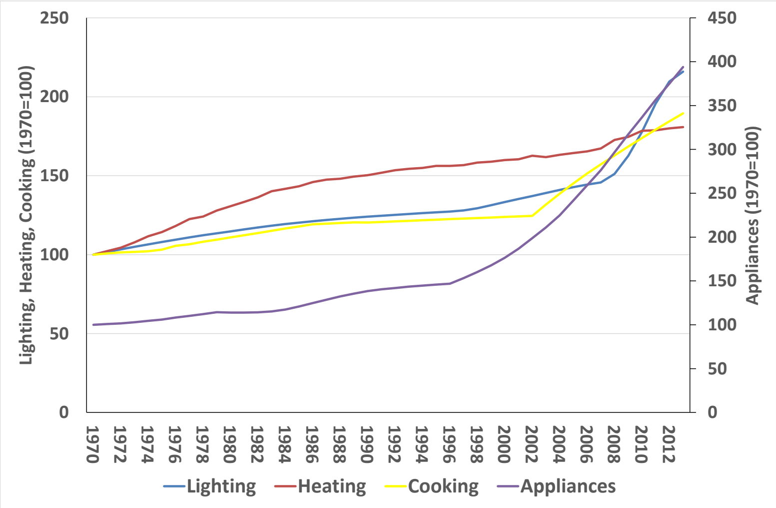

Figure 3 illustrates the trends in energy input prices for three categories of energy service. These trends represent the net impact of changes in the real price of energy commodities and changes in the mix of energy commodities used for each service (appliances and lighting are combined since they both use electricity alone). Energy input prices have fluctuated considerably over this period, with a steady decline between 1980 and 2004 and significant increases since that date. In real terms, energy input prices for heating and lighting are estimated to be around 60% higher in 2013 compared to 1970, while energy input prices for cooking are estimated to be around 20% higher.

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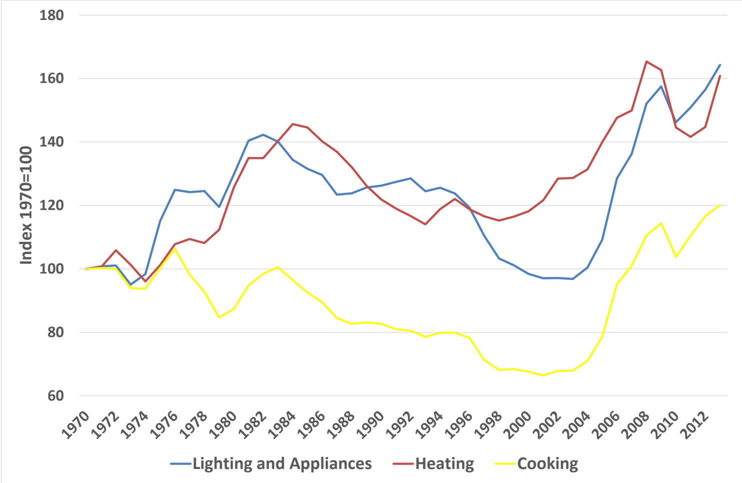
[14] Note that the axis for appliances is on the right-hand side of the figures.

Figure 3 Real price of energy for services in the UK 1970-2013 (index)



The real price of energy services depends upon both conversion efficiencies (Figure 2) and energy input prices (Figure 3). The resulting trends are illustrated in Figure 4. Between 1980 and 2002, a combination of falling energy prices and improving efficiencies led to significant reductions in the price of energy services. For lighting, heating and cooking this trend reversed after 2002, while for appliances the rate of reduction in service prices flattened out. In 2013, the real price of light was around 30% higher than in 1970, while the price of heating and cooking was around 10% lower and the price of 'appliance services' around 70% lower.

Figure 4 Real price of energy services in the UK 1970-2013 (index)

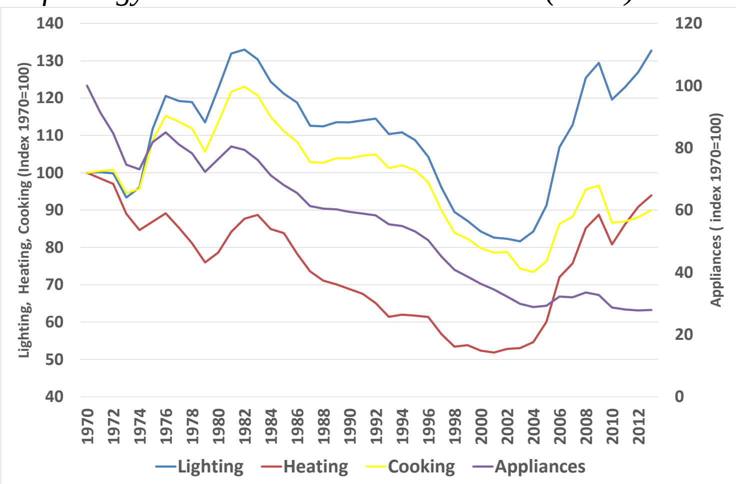
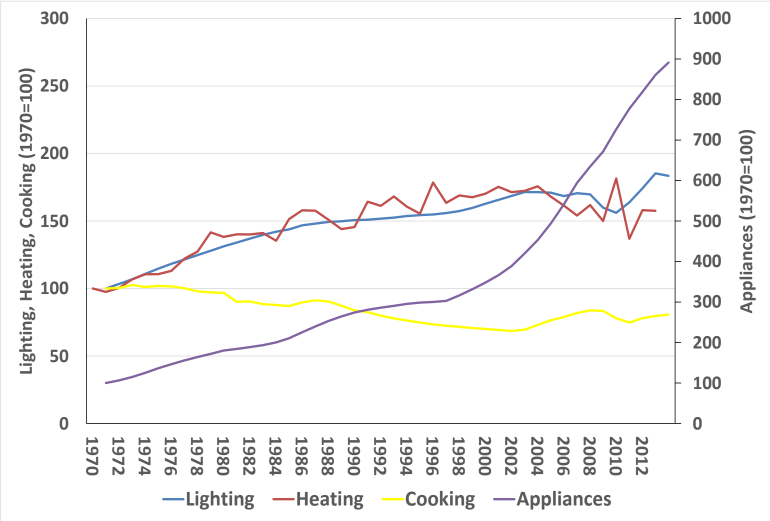


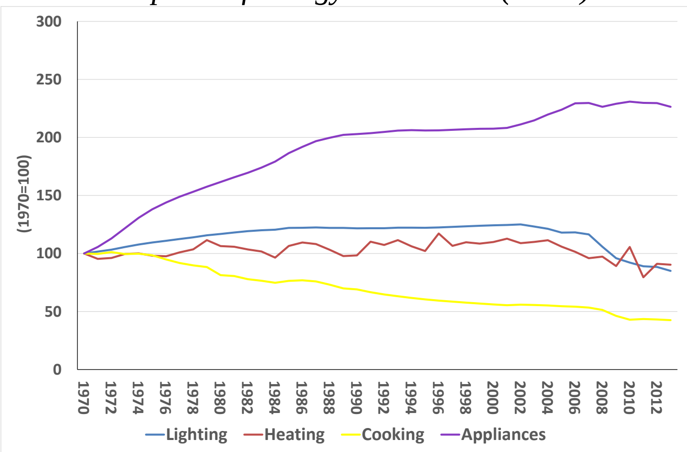
Figure 5 illustrates the resulting trends in household consumption of energy services over this period. Consumption of heating is estimated to have increased by ~60% over this period, while consumption of lighting has increased by ~80% and consumption of 'appliance services' by a staggering 900% - reflecting both greater use of wet and cold appliances and the explosion in electronic devices over the last 20 years. In contrast, consumption of cooking is estimated to have fallen by around 20% - perhaps reflecting greater reliance upon ready-meals and related trends.

Figure 5 UK household consumption of energy services 1970-2013 (index)



Finally, Figure 6 illustrates the estimated trends in energy consumption for each service. Efficiency improvements have mitigated (as well as partly contributed to) the increased consumption of heating and lighting, with the result that energy use for these services is ~20% lower than in 1970. For cooking, improvements in efficiency have combined with reductions in cooking demand to lead to a ~60% reduction in energy consumption. For appliances, efficiency improvements have moderated but not offset the rise in service demand, with the result that energy consumption for appliances is estimated to be ~230% higher than in 1970.

Figure 6 UK household consumption of energy 1970-2013 (index)



5 Results

The two-stage budgeting model in Figure 1 leads to five equations in two groups. The equations in each group are estimated as a system using the Iterative Seemingly Unrelated Regressions (ISUR) which is suitable for imposing cross-equation restrictions and corrects the estimates for any correlation of the error terms between equations. The equations in each group are estimated with homogeneity and symmetry restrictions imposed.[15] The adding up restriction is imposed by dropping one of the equations in each group.

Table 3 summarises the parameter estimates for the first stage equations, while Table 4 summarises the estimates from the second state (energy services group). The fit of the second-stage equations is good with more than 80% of the parameter estimates being statistically significant at the 5% level and each equation having an adjusted R^2 of ~90% or more. The fit of the first stage equations is poorer, but one third of the parameter estimates are significant at the 5% level and the adjusted R^2 exceed 75%. We also apply the Portmanteau test for each group and find no evidence of serial correlation.

To interpret the results we need to derive the elasticity estimates. Table 5 and Table 6 indicate the *between-group* elasticity estimates from the first stage, while Table 7 and Table 8 indicate the *within-group* estimates from the second stage (energy services group). These are inserted into the equations in Table 1 to provide estimates of the *total* expenditure ($\eta_{q_i x}$) and price ($\eta_{q_i p_j}$) elasticities for our four energy services (Table 9 and Table 10). The total price elasticity estimates are then inserted into Equation 13 to derive estimates of the direct, indirect and total rebound effects for our four energy services (Table 11 and Table 12).

From Table 9 we observe that the estimated expenditure elasticities for the energy services are relatively high, with heating being a 'luxury' good (i.e. $\eta_{q_i x} > 1$). This contrasts with Chinis and Sorrell [33] who found relatively low expenditure elasticities for the energy commodities supplying those services. Efficiency improvements may partly explain this difference, but other factors are likely to be influencing the results. Very few studies estimate expenditure elasticities for these energy services, but we observe that our estimate of the expenditure elasticity of lighting is approximately twice that found for the UK by Fouquet [34] (year 2000 estimate), while our estimate of the expenditure elasticity of heating is approximately 40% larger.

The estimated own price elasticities for the energy services are indicated in the main diagonal of Table 10 (in bold). These all have the expected sign and are surprisingly high for lighting (-0.84)), appliances (-0.63) and cooking (-1.0) but much lower for heating (-0.14). Again, few studies provide comparable estimates for the first three energy services, but we observe that our estimate of the own price elasticity of lighting is approximately twice as large as that found by Fouquet [34] (year 2000). In contrast, our estimate of the direct rebound effect for heating appears comparable to or lower than most estimates in the literature [1,2,35].

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[15] We also estimated the equations in each group without imposing homogeneity and symmetry restrictions, and used a Wald test to test for these restrictions both individually and in combination. Both the homogeneity and symmetry were rejected for the 'energy group' and symmetry was rejected for all groups. However, it is common for these restrictions to be rejected in demand models. As Edgerton [20] notes: "… this should not be taken as an indication of a failure of the laws of demand, since the Slutsky conditions are derived at the micro level and only invariant to aggregation under very special assumptions. The elasticities calculated from the model therefore must be interpreted as 'aggregate' elasticities and not micro elasticities coming from a representative consumer…." To ensure compatibility with consumer demand theory, we choose to impose the restrictions.

Table 10 also indicates the estimated cross-price elasticities between the four energy services. Looking first at the *signs* of the elasticities we observe that, for example, lighting is a complement to heating but a substitute for appliances and cooking. If correct, this would suggest that improvements in efficiency of lighting have encouraged increased heating as well as increased lighting - which is arguably consistent with the 'heat replacement effect' discussed in [5]. Since heating is GHG intensive and accounts for a significant proportion of total expenditure (i.e. ψ_i Equation 16 is relatively large) this cross-price response should *amplify* the overall rebound effect for lighting (i.e both the direct rebound effect for lighting and indirect rebound effect associated with heating will be positive). Other energy services (e.g. heating and appliances) are estimated to be substitutes, however, implying that improvements in the efficiency of one will lead to reductions in the consumption of the other. The resulting fall in emissions associated should *reduce* the overall rebound effect from the efficiency improvement (i.e. the direct rebound effect from lighting will be positive but the indirect rebound effect associated with appliances will be negative).

Looking next at the estimated *magnitude* of these elasticities, we observe that several of them are remarkably large. The results suggest, for example, that 1% reduction in the price of lighting will be associated with a 0.7% increase in consumption of appliance services. Cross-price responses of this magnitude are rather difficult to explain, and potentially suggest a problem with the analysis.

The estimates of the own price elasticities of each energy service translate directly into estimates of the direct rebound effect for those services (Table 12). Three of these estimates are very high compared to others in the literature, namely 63% for appliances, 84% for lighting and 100% for cooking. However, the estimate for heating is much lower (17%).

The indirect rebound effects are estimated with Equation 16, using 2013 values for the GHG intensities and expenditure shares of energy services. Table 11 summarises the rebound effect associated with each individual energy service, while Table 12 summarises the resulting estimates for direct, indirect and total rebound effects. From Table 11 it is clear that: first, the majority of indirect rebound effects are *negative*, owing to the energy services being estimated to be substitutes; and second, these effects are *very large*, owing to the cross-price elasticities being estimated to be large. As can be seen from Table 12, the net effect is that the indirect rebound effects associated with other energy services *largely cancel out* the direct rebound effects associated with the energy service benefiting from the efficiency improvement. For example, the indirect rebound effect associated with lighting is estimated at -83.9%, almost completely cancelling out the direct rebound effect of +83.7%. Overall, the results suggest total rebound effects of 0.25% for lighting, 0.29% for heating, 3.61 % for appliances and 0.7% for cooking – very small indeed given the estimate size of the direct rebounds.

Table 3 Parameter estimates from stage 1

	α^r	β^r	γ^{rs}			λ^{rs}		$\bar{R}^2$
			Energy services	Transport	Other goods and services	Energy services	Transport	
Energy services	0.0059 (0.4723)	-0.0022 (-0.4828)	0.0292 (4.5584)**	-0.0004 (-0.0631)	-0.0288	0.3609 (2.8821)**	0.0846 (1.1468)	0.84
Transport	0.0407 (2.7257)**	0.0017 (0.2838)	-0.0004 (-0.0631)	0.0218 (1.3509)	-0.0213	0.0820 (0.5720)	0.7191 (8.1568)**	0.73
Other goods and services	0.9534	0.0004	-0.0288	-0.0213	0.0501	-0.4429	-0.8037	_

Notes:

- *t*-values in parenthesis. ** and * indicate statistical significance at 5% and 10% probability levels respectively.
- Coefficients for 'other goods & services' are estimated from the adding-up and homogeneity restrictions.
- The lagged budget share of 'other goods & services' is dropped to avoid co-linearity.

Table 4 Parameter estimates from stage 2 – energy services group

	α_i^r	β_i^r	γ_{ij}^r				λ_{ij}^r			$\bar{R}^2$
			Lighting	Heating	Appliances	Cooking	Lighting	Heating	Appliances	
Lighting	-0.9667 (-6.6956)**	-0.0239 (-3.1787)**	0.0061 (1.1786)	-0.0493 (-6.1770)**	0.0295 (3.9671)**	0.022	0.9121 (4.4894)**	0.5903 (5.3165)**	0.6170 (5.8703)**	0.95
Heating	4.1575 (9.9764)**	0.1211 (5.2237)**	-0.0493 (-6.1770)**	0.1625 (6.1414)**	-0.0817 (-4.5236)**	-0.042	-0.4466 (-0.8780)	-2.0926 (-6.5505)**	-2.9432 (-9.8186)**	0.89
Appliances	-2.2883 (-6.7148)**	-0.0734 (-4.5325)**	0.0295 (3.9671)**	-0.0817 (-4.5236)**	0.0298 (1.6380)	0.026	0.3163 (0.8492)	1.8049 (7.2884)**	2.6272 (10.8054)**	0.97
Cooking	0.0975	-0.0158	0.0225	-0.0419	0.0263	-0.007	-0.7818	-0.3026	-0.301	-

Notes:

- Coefficients for 'cooking' are estimated from the adding-up restriction.
- The lagged budget share of 'cooking' is dropped to avoid co-linearity.

Table 5 Between-group expenditure elasticities ($\eta_{q_r x}$)

	Expenditure elasticity
Energy services	0.927
Transport	1.012
Other goods and services	1.001

Table 6 Between-group price elasticities ($\eta_{q_r p_s}$)

	Energy services	Transport	Other goods and services
Energy services	-0.013	-0.005	-0.910
Transport	-0.003	-0.846	-0.163
Other goods and services	-0.070	-0.195	-1.940

Table 7 Within-group expenditure elasticities ($\eta^r_{q_i,x_r}$)

	Expenditure elasticity
Lighting	0.615
Heating	1.201
Appliances	0.722
Cooking	0.667

Table 8 Within-group price elasticities ($\eta^r_{q_i,p_j}$)

	Price elasticity			
	Lighting	Heating	Appliances	Cooking
Lighting	-0.877	-0.561	0.577	0.246
Heating	-0.094	-0.851	-0.189	-0.066
Appliances	0.128	-0.140	-0.814	0.104
Cooking	0.216	-0.252	0.409	-1.041

Table 9 Total expenditure elasticities for energy services ($\eta_{q_i,x}$)

	Expenditure elasticity
Lighting	0.571
Heating	1.114
Appliances	0.669
Cooking	0.619

Table 10 Total price elasticities for energy services (η_{q_i,p_j})

	Price elasticity			
	Lighting	Heating	Appliances	Cooking
Lighting	**-0.839**	-0.195	0.738	0.289
Heating	-0.021	**-0.137**	0.126	0.016
Appliances	0.173	0.290	**-0.625**	0.153
Cooking	0.257	0.145	0.584	**-0.995**

Table 11 Rebound effects between energy services

	Lighting	Heating	Appliances	Cooking
Lighting	84.0%	18.5%	-73.8%	-28.4%
Heating	2.2%	13.7%	-13.8%	-1.8%
Appliances	-17.3%	-26.5%	62.5%	-15.1%
Cooking	-26.2%	-13.3%	-59.3%	99.5%

Table 12 Direct, indirect and total rebound effects for energy services (R_D , R_I and R_T)

	Direct rebound	**Indirect rebound**	**Total rebound**
Lighting	83.9%	-83.7%	0.25%
Heating	13.7%	-13.4%	0.29%
Appliances	62.5%	-58.9%	3.61%
Cooking	99.5%	-98.8%	0.70%

6 Summary

This study has sought to estimate the combined direct and indirect rebound effects from energy efficiency improvements in the delivery of heating, lighting, appliance and cooking services to UK households over the period 1972 2013. Rebound effects have been estimated in terms of the 'direct' GHG emissions associated with energy consumption, and the 'embodied' emissions associated with global supply chains have been ignored. The approach relies upon a unique database of the price and consumption of these energy services in the UK. To our knowledge, this is the first study of its type to estimate both own and cross-price elasticities between household energy services in the UK, as well as the first to use these to estimate rebound effects. In doing so, the study seeks to improve upon earlier work by Chitnis and Sorrell [10], since it does not rely on the assumption that the own-price elasticity of energy service demand is equal to the own-price elasticity of energy demand.

The results suggest, first, that the *direct* rebound effects from energy efficiency improvements over this period have been relatively large – for example, 83% for lighting and 62% for electric appliances. While few other studies have estimated these effects, our estimates are at the high end of the range found in the literature.

Second, the results suggest that the *indirect* rebound effects associated with other energy services are *equally large* but mostly *negative*. For example, the estimated indirect rebound effect associated with energy efficient lighting is almost the same in magnitude as the estimated direct rebound effect, but opposite in sign. As a result, these two effects largely cancel each other out, leading to total rebound effects of 3% or less for each energy service.

The source of these results is that most energy services are estimated to be *substitutes* - implying that increased consumption of one service will lead to reduced consumption of another. Since the energy services are comparable in terms of expenditure share and greenhouse gas intensity, the net result is that the increased emissions from greater use of one will be offset by reduced emissions from lesser use of others. The reason that direct and indirect effects are comparable in magnitude is that our estimates of the cross-price elasticities between the energy services are surprisingly large. This potentially suggests a problem with our results, but if so the source of this problem remains unclear. We are currently investigating the robustness of the results, together with alternative ways of formulating the model, and we therefore emphasise that **the results presented here should be treated as provisional.**

There are a number of further caveats to the results. First, there are considerable difficulties in compiling time series estimates of the price and consumption of energy services, and the resulting uncertainties limit our level of confidence. Second, constraints on degrees of freedom in the econometric model create a number of problems, including: limiting the feasible level of disaggregation of household expenditure; preventing us from including socio-economic covariates; and requiring us to impose separability assumptions. Each of these could also bias the results. Third, our estimates of own-price elasticities are also relatively high, and higher than those found in earlier work by Fouquet[36], despite using a similar data source. Lower estimates of these elasticities would lead to lower estimates of the direct rebound effect.

We further note that our study neglects the indirect rebound effects associated with induced changes in transport demand, together with the rebound effects associated with embodied emissions and other, non-energy goods and services. Although the sign of these effects is ambiguous, their inclusion could would necessarily change our estimates of the total rebound effect.

Planned future work will address several of the above limitations. In particular, we plan to include a disaggregated breakdown of transport services within the demand model (distinguishing between car, bus and train travel), since we expect this to have the biggest impact on the overall rebound effect.

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