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Living up to expectations: Estimating direct and indirect rebound effects for UK households

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ABSTRACT

This study estimates the combined direct and indirect rebound effects from various types of energy efficiency improvement by UK households. In contrast to most studies of this topic, we base our estimates on cross-price elasticities and therefore capture both the income and substitution effects of energy efficiency improvements. Our approach involves estimating a household demand model to obtain price and expenditure elasticities of different goods and services, utilising a multiregional input–output model to estimate the GHG emission intensities of those goods and services, combining the two to estimate direct and indirect rebound effects, and decomposing those effects to reveal the relative contribution of different mechanisms and commodities. We estimate that the total rebound effects are 41% for measures that improve the efficiency of domestic gas use, 48% for electricity use and 78% for vehicle fuel use. The primary source of this rebound is increased consumption of the cheaper energy service (i.e. direct rebound) and this is primarily driven by substitution effects. Our results suggest that the neglect of substitution effects may have led prior research to underestimate the total rebound effect. However, we provide a number of caveats to this conclusion, as well as indicating priorities for future research.

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.

Studies of rebound effects for consumers typically focus upon the *direct* effects that result from increased consumption of cheaper energy services. For example, fuel-efficient cars make driving cheaper so people may drive further and/or more often (Small and Van Dender, 2007; Sorrell, 2007). But a comprehensive accounting of the global environmental impact of energy efficiency improvements must also take into account various *indirect* rebound effects. For example, any savings on fuel bills may be put towards increased consumption of other goods and services whose provision also involves energy use and emissions at different stages of their global supply chains (Chitnis et al., 2013; Druckman et al., 2011). To quantify indirect rebound effects, it is necessary to combine econometric analysis of household (re)spending patterns with estimates of the energy and emissions 'embodied' within different categories of goods and services. The latter, in turn can be derived from environmentally extended, multiregional input–output models (Druckman and Jackson, 2009; Turner et al., 2007; Wiedmann et al., 2007).

Relatively few studies estimate both direct and indirect rebound effects and most of these rely upon expenditure elasticities rather than cross-price elasticities. As a result, they capture the *income* effects of energy efficiency improvements but not the *substitution* effects (Chitnis et al., 2014). To appreciate the distinction, consider a household that installs insulation and recovers the capital costs over ten years through lower heating bills. Since the bill savings exactly offset the capital costs, the investment provides no increase in real income over this period—so the income effect is zero. Hence, studies that focus solely upon income effects would estimate the direct and indirect rebound effects over that period to be zero as well. But since the unit cost of heating has fallen relative to that of other goods and services, the household is likely to consume more heating and fewer goods and services that are 'substitutes' to heating. At the same time, the household may consume more of other goods and services that are 'complements' to heating. The net result will be a shift in consumption patterns and hence a change in the GHG emissions associated with that consumption that may offset the original emission savings. Hence, it is possible that studies that neglect substitution will underestimate rebound effects.

This study therefore addresses the limitations of the existing literature by (a) estimating the magnitude of both direct and indirect rebound effects following the adoption of energy efficiency measures by households; (b) identifying the relative contribution of income and

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substitution effects to these results; and (c) identifying the relative contribution of individual goods and services. This is the first study to estimate these effects for UK households, as well as the first to decompose them to this level of detail.

The paper is structured as follows. Section 2 introduces the relevant concepts, highlights some methodological trade-offs and summarises the existing literature. Section 3 outlines the methodology, including the data sources used, the economic model adopted and the econometric techniques employed. Section 4 presents the results, including the estimates of direct and indirect rebound effects and the contribution of different mechanisms and commodities to those effects. Section 5 concludes by discussing the robustness of the results, their implications and the priorities for future work.

2. Concepts and previous work

2.1. Direct 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 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

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

As shown by Sorrell and Dimitropoulos (2007a), this may be written as[1]

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

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) (Sorrell and Dimitropoulos, 2007a):

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

If the energy service is a normal good ($\eta_{q_s,p_s} \leq 0$) there will be a positive direct rebound effect ($R_D \geq 0$). This may be decomposed into a *substitution* effect and an *income* effect[2] using the Slutsky equation:

$$\eta_{q_s,p_s} = \tilde{\eta}_{q_s,p_s} - w_s \eta_{q_s,x} \tag{4}$$

where w_s is the share of the energy service in total household expenditure (x); $\eta_{q_s,x}$ is the expenditure elasticity of the energy service; and $\tilde{\eta}_{q_s,p_s}$ is the *compensated* own-price elasticity of demand for the energy service, holding utility constant. The income ($\hat{R}_D$) and substitution ($\tilde{R}_D$) components of the direct rebound effect are then as follows:

$$\hat{R}_D = w_s \eta_{q_s,x} \tag{5}$$

$$\tilde{R}_D = -\tilde{\eta}_{q_s,p_s} \tag{6}$$

$$R_D = \hat{R}_D + \tilde{R}_D \tag{7}$$

Income and substitution effects may either offset or reinforce one another (Table A.1). If estimates of η_{q_s,p_s} are available the direct rebound effect can be derived, and if estimates of $\eta_{q_s,x}$ are also available, it can be decomposed. In contrast, if only estimates of $\eta_{q_s,x}$ are available, then only the income effect can be obtained. This will form a biased estimate of the direct rebound effect since substitution effects will be overlooked.

2.2. Indirect rebound effects

Energy efficiency improvements may also change the quantity demanded of other goods and services. These include both other energy services (e.g. heating) and other non-energy goods and services (e.g. furniture) that 'embody' the energy and emissions required to manufacture and deliver them. These changes in consumption patterns will impact energy use and emissions at each stage of the relevant supply chains. From a global perspective, these changes may either offset or add to the energy and emission savings from the energy efficiency improvement depending on whether the quantity demanded of the relevant goods or service has increased or fallen. The *indirect rebound effect* (R_{I_i}) from an individual commodity (i) will be proportional to this change in energy and emissions, which in turn will depend upon the energy or emissions intensity of the commodity relative to that of the energy service; and the elasticity of demand for that commodity with respect to the price of the energy service. The latter is defined as

$$\eta_{q_i,p_s} = \frac{\partial \ln q_i}{\partial \ln p_s} \tag{8}$$

Again, this elasticity can be decomposed:

$$\eta_{q_i,p_s} = \tilde{\eta}_{q_i,p_s} - w_s \eta_{q_i,x} \tag{9}$$

where w_s is the share of the energy service in total household expenditure; $\eta_{q_i,x}$ is the expenditure elasticity of commodity i; and $\tilde{\eta}_{q_i,p_s}$ is the compensated elasticity of demand for commodity i with respect to the energy cost of the energy service. The substitution effect for commodity i ($\tilde{\eta}_{q_i,p_s}$) may offset or reinforce the income effect ($-w_s \eta_{q_i,x}$) for that commodity (Table A.2). Consumption of commodities that are complements (substitutes) to the energy service will increase (reduce) following the energy efficiency improvement. The impact of this on emissions will depend upon the emissions intensity of each commodity. If estimates of both η_{q_i,p_s} and $\eta_{q_i,x}$ are available the indirect rebound effects for each commodity can be derived and decomposed ($R_{Ii} = \hat{R}_{I_i} + \tilde{R}_{Ii}$), but if only estimates of $\eta_{q_i,x}$ are available, only the income effect can be obtained. To estimate the overall indirect rebound effect we need to sum the corresponding change in emissions over all commodities ($R_I = \sum_i R_{I_i}$).

2.3. Estimating direct and indirect rebound effects

To estimate direct and indirect rebound effects we need estimates of the own- and cross-price elasticities for the relevant energy service. This requires the estimation of 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 one of these commodities being the energy service (s).

A growing number of studies estimate own-price elasticities for individual energy services (η_{q_i,p_s}), but to our knowledge, no study has estimated cross-price elasticities (η_{q_i,p_s}) owing to the difficulties of specifying energy services as a 'commodity' within a household demand model (Sorrell, 2010). Since energy services are produced from a combination of energy commodities (e.g. gas) and durable goods (e.g. boilers), specifying their energy cost (p_s) and quantity demanded (q_s) involves combining data on energy commodity purchases with additional data on the ownership and energy efficiency of the relevant durables (Conrad and Schröder, 1991). Since this data may not be

[1] 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, $\eta_{q_e,\varepsilon} = -\eta_{q_s,p_s} - 1$.

[2] The former is the change in consumption that would result from the change in relative prices if real income were adjusted to keep utility constant, while the latter is the change in consumption that would result exclusively from this change in real income.