The rebound effect: to what extent does it vary with income?

Mona Chitnis[1,*], Steve Sorrell[2], Angela Druckman[1] and Steven Firth[3]

[1]Centre for Environmental Strategy, University of Surrey

[2] Science and Technology Policy Research, University of Sussex

[3]School of Civil and Building Engineering, Loughborough University

***Corresponding author:** Sustainable Lifestyles Research Group (SLRG), Centre for Environmental Strategy, University of Surrey, Guildford, Surrey, GU2 7XH, UK.

Tel. +44 (0) 1483 682181, Fax. +44 (0) 1483 686671, Email: M.Chitnis@surrey.ac.uk

Abstract

Policymakers expect improved energy efficiency and abatement actions to play a key role in reducing GHG emissions. However, the energy and emissions reductions from such measures may be less than expected because of 'rebound effects'. In this paper, a number of energy efficiency improvements and abatement actions are simulated for heating, lighting, transport and food related measures. Using expenditure elasticities from Engel curves estimated from 2009 cross-section data; average direct and indirect rebound effects are estimated over a ten year period for UK households divided into income quintiles. Results show that rebound is generally higher for lower income groups, with the magnitude of the rebound effect varying widely according to the measure, the cost of implementation and the embodied GHGs involved. Rebound effects tend to be relatively moderate for heating and lighting measures but are significantly larger for transport measures. Government subsidies offset capital costs and increase the rebound effects, but without subsidies low income groups would often not be able to implement the energy efficiency measures and face fuel poverty. Therefore, even though rebound effects exist, results show that because it is generally less than 100%, the measures are still worthwhile.

Keywords: rebound effects, Engel curve, energy efficiency, abatement, households.

1. Introduction

The UK government has a target of 80% reduction in greenhouse gas (GHG) emissions by 2050 (HM Government 2008). In order to achieve this target, various policies are being applied including the use of energy efficiency measures and energy abatement actions through behavioural changes by households. The hope is to reduce household energy consumption and associated GHGs, hence moving towards lower GHG emissions. The government has even introduced subsidies to lower the cost for a number of energy efficiency measures to encourage households to apply such measures. However, as the result of 'rebound effects', the expected reduction in energy consumption and associated GHGs might not fully achieved. This phenomenon is generally ignored in government policy considerations.

The improved energy efficiency reduces the price of the relevant energy service, as the same amount of energy service now needs less units of energy.[1] As the price of energy service is now lower, households increase their consumption of this energy service while may decrease or increase the consumption of other goods and services[2] (substitution effect). Alongside this, the lower energy service price results in an increase in real income which allows households to consume more of the same energy service and also additional other goods and services[3] (income effect). Overall effect increases the consumption of the relevant energy service offsetting the expected GHG reduction due to the energy efficiency improvement[4]; this is called 'direct rebound

[1] See Sorrell (2010) for more details.

[2] This depends on whether other goods and services are substitute or complement to the relevant energy service.

[3] All the goods and services are assumed to be 'normal'.

[4] Assuming the demand for the relevant energy service were to remain constant.

effect'. The overall effect may increase or decrease the consumption of other goods and services hence associated GHGs affecting the expected reduction in GHG reduction[5]; this is called 'indirect rebound effect'.

For abatement actions, there is no direct rebound effect as the household decides to consume less from a particular energy service; however, the indirect rebound effect exists. For energy efficiency measures, therefore, the size of total rebound effect (direct and indirect rebound) is important in policy making; a higher rebound effect implies that there will be a greater gap between emissions reduction targets and the emissions reductions achieved in reality. The remainder of this paper is organised as follows:

Section 2 gives some background of previous studies on rebound effects. Section 3 presents the methodology for estimation of rebound effects and Engel curves. Section 4 describes the data and assumptions. Section 5 presents the Engel curves and rebound results. Section 6 is the discussion of the results and the conclusion.

2. Background

Despite the importance of the rebound effect in policy decisions, there is still a limited number of studies attempted to quantify the rebound effect[6]; either 'direct' or 'indirect' or 'both'; for households. This is partly due to data availability and difficulties in precise estimation of rebound for a particular energy efficiency measure or abatement action. In Druckman et. al. (2011), we estimated the 'indirect' GHGs

---

[5] Assuming demand for these goods and services were to remain unchanged.

[6] See Chitnis et. al. (2012) for samples of empirical rebound studies.

rebound effects for UK average household for three abatement actions: lowering the heating thermostat by 1^{o}C, eliminating the food waste by one third, walking or cycling instead of using a car for trips of less than 2 miles. The abatement actions did not involve any cost. The reduced expenditure in the relevant consumption categories was allocated between expenditure for 'other goods and services' and 'household saving', using the income elasticities and saving ratio, and were combined with estimates of the GHG intensity of different categories of goods and services to estimated the rebound from the 'consumption perspective'.[7]

In Chitnis et. al. (2012), with the focus on income effects, we developed the above study by estimating both 'direct and indirect' GHGs rebound effects averaged over a ten year period for a number of energy efficiency improvement measures in homes for an average UK household. The measures included cavity wall insulation, loft insulation, condensing boiler installation, tank insulation, efficient lighting (CFL and LED) and solar thermal. The above measures involved capital costs could offset the reduced expenditure. On the other hand, the provision of such measures involve embodied energy[8] hence 'embodied GHGs' associated with them. In this study, the embodied GHGs are regarded as offsetting some of the expected GHG reduction from

[7] The 'consumption perspective', includes emissions that arise overseas and are 'embodied' in the production and distribution of goods and services consumed in the UK, but excludes those that arise within the UK in the production of goods and services exported abroad. Arguably, the consumption perspective is more appropriate, as opposed to 'production perspective', for consideration of policies concerning household consumption (see Druckman and Jackson 2009a for further details). In the current paper, rebound effects for GHGs are estimated from the consumption perspective.

[8] 'Indirect energy' or 'embodied energy' is the energy used in supply chains in the production and distribution of goods and services purchased by UK households.

the energy efficiency measure hence contributing to an increase in the rebound effect. Using a similar approach to Druckman et. al. (2011), we investigated how allowing for the capital cost and embodied GHGs of the relevant measure can affect the rebound results obtained.

Although the above studies give insight into the magnitude of rebound effects, they solely estimate rebound for an average UK household. However, rebound effects are expected to vary between different household income groups. In particular, rebound is expected to be higher for lower income groups. This is due to the relatively high proportion of their expenditure in energy and food categories, and also because they are expected to spend a higher proportion of any additional income on essentials such as energy and food than higher income groups who are more likely to spend it on luxury goods. There are limited numbers of studies, as far as known, that attempt to estimate direct and indirect rebound effects by household income groups.

Murray (2011) estimates the direct and indirect rebound effects from reduced vehicle use, reduced electricity use, and the adoption of energy efficient vehicles and the adoption of energy efficient electrical lighting. He uses Australian household expenditure 2003-2004, aggregated into 36 commodity groups, and embodied GHG emissions data calculated using a published input-output based hybrid method. Double semi-log (DSL), linear and Working-Leser (WL) functional forms of Engel curves are estimated using Ordinary Least Square (OLS) econometric method to obtain expenditure elasticities for each category of commodities. In this study, the total embodied energy in the more efficient appliance is subtracted from the potential energy use reductions, because in Murray's view this embodied resource consumption is necessary and inseparable from the technology itself. He finds that the total direct and indirect rebound decreases with increasing income. For the vehicle efficiency case, the total rebound effect is in the range of 11% to 48%. The electricity efficiency total rebound is between 3% and 10%. For households undertaking combined efficiency measures, the rebound effect is between 10% and 30% across the income range.

Thomas et. al. (2012) simulates direct and indirect rebound effects in primary energy, CO2e, NOx, and SO2 emissions for the average U.S. household for a hypothetical energy efficiency investment that either reduces electricity, natural gas, or gasoline expenditures. Using a direct rebound effects parameter, they model the indirect rebound effects using properties of elasticities and a partial equilibrium (fixed-price) economic input-output lifecycle assessment model of household re-spending patterns from the 2004 U.S. Consumer Expenditure Survey. However, they use the estimates for price and expenditure elasticities and emission intensities from the literature and other sources. They find that direct and indirect rebound effect varies by household income, with lower-income groups having a slightly higher CO2e rebound. The direct and indirect rebound effect for electricity and gasoline efficiency vary between 35%-60% and 15%-25% for various income brackets respectively.

In this paper, again focusing on income effects for simplicity, all of the energy efficiency improvement measures and abatement actions in previous two papers plus the use of a 'fuel-efficient car' are simulated by UK households. The resulting direct and indirect GHGs rebound effects are estimated for different income groups (quintiles) using the expenditure elasticities of different goods and services for each income group. In order to estimate the expenditure elasticities by income groups, the

Engel curves (similar to Murray 2011) are estimated for 16 categories of goods and services using UK household cross-section data in 2009. In addition to estimation of expenditure elasticities by income groups, the use of cross-section data as opposed to time series data in our previous papers, allows for inclusion of socio-demographic variables in the model.

Finally, where embodied GHGs exist for energy efficiency measure, the rebound estimation can be based on two different definition of rebound formula: a. embodied GHGs regaded as offsetting some of the expected GHG reduction from the energy efficiency measure hence contributing to an increase in the rebound effect (e.g. Chitnis et. al. 2012) and b. the embodied GHGs is subtracted from the potential savings in GHGs hence contributing to a decrease in the rebound effect (e.g. Murray 2011). In Chitnis et. al. (2012), only one of these definitions i.e. (b) was used to estimate rebound. In this paper, both definitions of rebound formula are used for estimation and the results are compared.

3. Methodology

This section explains the definition of rebound effect and the approach used for estimation.

3.1. Estimation of rebound effect

The estimated rebound effect is the result of three different effects which, in this paper, are labelled as the ‘engineering effect’, ‘embodied effect’ and ‘re-spending effect’.

3.1.1. Engineering effect

Each energy efficiency measure is expected to reduce the amount of energy required to deliver a given level of energy service (e.g. heating, lighting). If the demand for energy services were to remain unchanged, there would be a corresponding reduction in household electricity and/or fuel use and the GHG emissions associated with this consumption. Similarly, each abatement action (e.g. reducing food waste) is expected to reduce the demand for the relevant good or service and the GHG emissions associated with this good or service. The average engineering effect (ΔH_t) per household is an estimate of reduction in GHG emissions due to the energy efficiency measure, assuming that the demand for energy services remains unchanged, or abatement action as follows:

$$\Delta H_t = \sum_f s_{ft} \Delta E_{ft} \tag{1}$$

where s_{ft} is the GHG intensity of good or service f, ΔE_{ft} is the change in average annual reduction in demand for good or service f per household and t is the time period (t = 1 to T).

3.1.2. Embodied effect

The 'embodied effect' (ΔM_t) is relevant for energy efficiency measures only. It is an estimate of the embodied emissions that are incurred in manufacturing and supplying the relevant energy efficient equipment and installing it in dwellings:

$$\Delta M_t = M_t - M'_t \tag{2}$$

where M_t is the average household embodied emissions for the energy efficiency measure (e.g. fuel-efficient car) and M'_t is the average household embodied emissions of the alternative; i.e. purchasing the less energy efficient equipment similar to the existing one (e.g. fuel-inefficient car).

3.1.3. Re-spending effect

Due to the energy efficiency measure or abatement action, household expenditure on the energy service or the relevant goods and services that is subject to the measure or action is reduced. Assuming the demand for the energy service remains unchanged, the avoided expenditure (ΔC_t) is:

$$\Delta C_t = \sum_f k_{ft} \Delta E_{ft} \quad (3)$$

where k_{ft} is the price per unit of energy or relevant goods and services.

However, in the case of energy efficiency measure, there is capital cost (ΔK_t) associated with the measure:

$$\Delta K_t = K_t - K'_t \quad (4)$$ [9]

where K_t is the average household capital cost for the energy efficiency measure and K'_t is the average household capital cost of the alternative.

The difference between ΔC_t and ΔK_t is assumed to be analogous to a change in household disposable income (ΔY_t):

$$\Delta Y_t = \Delta C_t - \Delta K_t \quad (5)$$

[9] For simplicity, we assume that the full capital cost of the measure is incurred in the year in which the measure is installed.

Households are assumed to divide their disposable income between the total expenditure (X_t) and saving (S_t) with a fixed saving rate in a given year ($\bar{r}_t$) such that:

$$\Delta S_t = \bar{r}_t \Delta Y_t \qquad (6)$$

The average household change in GHG emissions as a consequence of the change in disposable income or 're-spending effect' (ΔG_t) is given by:

$$\Delta G_t = \sum_{i=1}^{I} \left[u_{it} \Delta X_{it} \right] + u_{st} \Delta S_t \qquad (7)$$

where X_{it} represent the household expenditure on goods and services for category i (i = 1 to I) and u_{it} and u_{st} are the GHG intensities of expenditure for category i and saving respectively.

Using the expenditure elasticity (β_i) definition, the change in expenditure for each category of goods and services due to change in total expenditure, holding all other variables constant, is as follow:

$$\Delta X_{it} = \beta_i \frac{\Delta X_t}{X_t} X_{it} \qquad (8)$$

Substituting ΔX_{it} from Equation 8 into Equation 7 and replacing total expenditure and saving by their shares from disposable income from Equation 6:

$$\Delta G_t = \left[\frac{(1 - r_t)\Delta Y_t}{X_t} \right] \Sigma_{i=1}^{I} u_{it} \beta_i X_{it} + u_{st} r_t \Delta Y_t \qquad (9)$$

The Engel aggregation condition is defined by:

$$\sum_{i=1}^{I} \beta_i X_{it} = X_t \qquad (10)$$

It ensures that additional total expenditure will be precisely exhausted by households' expenditures in different categories of commodities. Equation 9 can therefore be written as follow:

$$\Delta G_t = \left[\frac{(1-r_t)\Delta Y_t}{\sum_{i=1}^{I} \beta_i X_{it}} \right] \Sigma_{i=1}^{I} u_{it} \beta_i X_{it} + u_{st} r_t \Delta Y_t \tag{11}$$

The expenditure elasticity for each category of goods and services in equation 11 is estimated through Engel curves by income quintiles and explained in section 3.2. This allows for estimating the rebound effects for households by income quintiles.

3.1.4. Rebound effect

The average rebound effect (*RE*) from the energy efficiency improvement or abatement action over a $t=1, \ldots, T$ year period can be defined as:

$$RE = \frac{(Expected\ savings - Actual\ savings)}{Expected\ savings} = -\frac{1}{\Delta H}(\Delta G + \Delta M) \tag{12}$$

where $\Delta H = \sum_{t=1}^{T} H_t$, $\Delta G = \sum_{t=1}^{T} G_t$ and $\Delta M = \sum_{t=1}^{T} M_t$.

The definition in equation 12 treats the embodied effect as offsetting some of the expected GHG reduction from the energy efficiency measure hence contributing to an increase in the rebound effect. However, some policy-makers might be aware of the embodied energy in various energy efficiency measures hence they may take account of it when they set their targets. In these cases the alternative definition of the rebound effect (*RE**) is more appropriate, in which the embodied effect is subtracted from the engineering effect:

$$RE^* = -\frac{\Delta G}{(\Delta H - \Delta M)} \qquad (13)^{10}$$

3.2. Engel curve

An Engel curve describes how household expenditure on a particular good or service varies with household income. To estimate the expenditure elasticity for each category of goods and services by household income quintiles, following Haque (2005), the Engel curve for each category is estimated using two different functional forms, WL and DSL. These are both described in the following paragraphs and we use estimations of both in this study.

a. Working-Leser (WL)

$$W_i = \alpha_i + \beta_i x + \gamma_i HRP + v_i \qquad (14)$$

where W_i is the equivalised budget share of expenditure category i, x is the logarithm of equivalised total expenditure and HRP is the age of household reference person. α_i, β_i and γ_i are the unknown parameters and v_i is the random error term. The adding-up condition in WL is as follows:

$$\sum_i \alpha_i = 1 \text{ and } \sum_i \beta_i = 0 \qquad (15)$$

[10] If a measure or action reduces GHG emissions by less than what engineering effect suggests then $RE, RE^* \leq 1$. If a measure or action reduces GHG emissions by more than what engineering effect suggests then $RE, RE^* < 0$. If a measure or action reduces GHG emissions equal to what engineering effect suggests then $RE, RE^* = 0$. It is possible, though unlikely, that a measure or action increases GHG emissions so that $RE, RE^* > 1$; an outcome that has been termed 'backfire'.

The adding up condition is satisfied automatically for WL when using OLS equation by equation estimation method, as done here.

The expenditure elasticity for each category is then derived as follows:

$$W_i = \frac{X_i}{X} \qquad (16)$$

where X_i and X are equivalised expenditure for category i and equivalised total expenditure respectively.

Taking logarithm from both sides of equation 16 and re-arranging:

$$LnX_i = LnW_i + LnX \qquad (17)$$

Replacing for W_i from equation 16:

$$LnX_i = Ln(\alpha_i + \beta_i LnX + \gamma_i HRP + v_i) + LnX \qquad (18)$$

From definition of expenditure elasticity ($\varepsilon_{X_i X}$):

$$\varepsilon_{X_i X} = \frac{\Delta X_i}{\Delta X} . \frac{X}{X_i} = \frac{\Delta LnX_i}{\Delta LnX} \qquad (19)$$

With regard to equation 17 and 18:

$$\varepsilon_{X_i X} = \frac{\Delta LnX_i}{\Delta LnX} = \left(\frac{\Delta LnW_i}{\Delta W_i}\right)\left(\frac{\Delta W_i}{\Delta LnX}\right) + 1 \qquad (20)$$

Given that $\frac{\Delta LnW_i}{\Delta W_i} = \frac{1}{W_i}$ and $\frac{\Delta W_i}{\Delta LnX} = \beta_i$, the expenditure elasticity, i.e. equation 20, for WL Engel curve over the whole sample is:

$$\varepsilon_{X_i X} = \frac{\beta_i}{W_i} + 1 \qquad (21)$$

The expenditure elasticity for each income quintile can then be obtained using:

$$\varepsilon_{X_{ij}X_j} = \frac{\beta_i}{\overline{W}_{ij}} + 1 \tag{22}$$

where X_{ij} is the equivalised expenditure of category i for quintile j, X_j is the total expenditure for quintile j and $\overline{W}_{ij}$ is the average equivalised budget share of expenditure category i for quintile j.

b. Double Semi-Log (DSL)

$$X_i = \lambda_i + \theta_i X + \varphi_i x + \rho_i HRP + \omega_i \tag{23}$$

where X_i is the equivalised expenditure for category i, X is equivalised total expenditure, x and HRP are defined above. λ_i, θ_i, φ_i and ρ_i are the unknown parameters and ω_i is the random error term. The adding-up condition in DSL is as follows:

$$\sum_i \lambda_i = 0 \text{ and } \sum_i \theta_i = 1 \tag{24}$$

The adding up condition is satisfied automatically for DSL when using OLS equation by equation estimation method.

Using the expenditure elasticity definition in equation 19 and given that $\frac{\Delta X_i}{\Delta X} = (b_i + \frac{c_i}{X})$, the expenditure elasticity for DSL Engel curve over the whole sample is:

$$\varepsilon_{X_i X} = \frac{\Delta X_i}{\Delta X} . \frac{X}{X_i} = \frac{1}{X_i}(b_i X + c_i) \tag{25}$$

The expenditure elasticity for each quintile can then be obtained using:

$$\varepsilon_{X_{ij}X_j} = \frac{1}{\overline{X}_{ij}}(b_i \overline{X}_j + c_i) \tag{26}$$

where $\overline{X}_{ij}$ and $\overline{X}_{j}$ are the average equivalised expenditure of category *i* for quintile *j* and average total expenditure for quintile *j*, respectively.

4. Data and assumptions

The rebound effects are estimated for a number of energy efficiency improvements including cavity and loft insulation; condensing boiler insulation; hot water tank insulation; efficient lighting (CFL and LED); a combination of the above measures; solar thermal; and fuel-efficient car. For lighting, two sets of estimates for energy efficient lighting measures is provided; the first allows for the EU ban on incandescent bulbs[11] while the second assumes instead that installing energy efficient lighting avoids subsequent use of GLS bulbs. The rebound effects are also estimated for some abatement actions including turning down the heating thermostats at homes by 1ºC from a default value of 21ºC to 20 ºC (hereafter 'household thermostat temperature reduction'), eliminating food waste by one third (hereafter 'food waste reduction'), walking or cycling instead of using a car for trips of less than 2 miles (hereafter 'car use reduction') and a combination of the three actions above. The data used for the rebound estimation of each measure is explained below.

4.1. Engineering effect

An engineering model called Community Domestic Energy Model (CDEM)[12] by Firth et. al. (2009) is used to estimate the energy consumption (in kWh) of the average

[11] For more information see: europa.eu/rapid/pressReleasesAction.do?reference=IP/08/1909

[12] The CDEM model has been developed at the University of Loughborough to simulate energy use in the English housing stock and to explore options for reducing CO_2 emissions.

English dwelling stock in 2009 by energy carrier[13] before and after the energy efficiency improvement or energy abatement is applied. This allows for estimation of the engineering effect for cavity and loft insulation, condensing boiler, tank insulation, efficient lighting (CFL and LED), a combination of above measures and turning down the heating thermostats by 1ºC. However, CDEM can not be used to simulate solar thermal heating, hence a variety of sources are used to make assumptions for the solar thermal measure. Relevant assumptions associated with CDEM, the GHG intensity of the relevant energy carriers and solar thermal can be found in Chitnis et. al. (2012). The assumptions for fuel-efficient car, food waste reduction and car use reduction are given in Appendix 1.

The percentage change in estimated GHGs due to the energy efficiency and abatement actions used for an 'average' UK household are summarised in Appendix 2: Table 2. These percentages are used to find ΔE_t for use in equation 1 and hence to estimate ΔH_t.[14]

4.2. Embodied effect

The abatement actions require no equipment. Therefore, there are no embodied emissions associated with these actions. For simplicity, it is assumed that efficient and inefficient cars both have similar embodied emissions and the embodied GHGs are zero. The relevant assumptions for the embodied GHG emissions associated with all

[13] The relevant energy carriers are gas, oil, solid fuels and electricity.

[14] The GHG intensity in each category is multiplied by expenditure in the same category to obtain the associated GHG. See section 3.3 for GHG intensities data.

the other measures are explained in Chitnis et. al. (2012), and the values used in this study are summarised in Table 3 of Appendix 2.

4. 3. Re-spending effect

The re-spending effect is estimated using the cost savings from each measure (ΔC_t), the capital cost of each measure (ΔK_t), the expenditure elasticity of each commodity category (β_i) and the GHG intensity of each expenditure category and household saving (u_{it} and u_{st}). The relevant assumptions for the above are given below:

Cost savings

Use of a more efficient vehicle enables cost savings both with regards to expenditure on fuel and also vehicle tax, as cars with low emissions incur a lower tax rate[15] (add reference). These cost savings per car presented in Table 5 in Appendix 2 are estimated using the assumptions in Tables 1 and 4 in Appendix 2.[16, 17]

Estimated cost savings for the abatement actions are as explained in section 4.1. Estimates of the energy cost savings from all other measures are derived by using the CDEM and assumed unit price of the relevant energy carriers given in Chitnis et. al.

---

[15] www.direct.gov.uk/en/Motoring/OwningAVehicle/HowToTaxYourVehicle/DG_10012524

[16] The cost saving is calculated for all diesel cars and then divided by total number of cars to obtain the average vehicle fuels cost saving for one car.

[17] 'Vehicle fuels' expenditure category used in this paper does not include car tax. Therefore, the expenditure saving due to vehicle fuel efficiency is estimated separately and the cost saving due to tax is added to this to obtain the total cost saving for efficient car measure.

(2012). The estimated percentage change in total energy expenditure[18] from the different measures and actions for an 'average' English dwelling is presented in Table 5 in Appendix 2.

Capital costs

As with the embodied effect, it is assumed that the capital cost of replacing an existing fuel-inefficient car with a fuel-efficient car is zero. There is no capital cost for the abatement actions as they require no equipment to be purchased. Estimates for the capital cost of all other measures are largely based upon information provided by the UK government (DECC 2010) presented in Chitnis et. al. (2012), and the capital cost estimates are summarised in Appendix 2: Table 6.

Expenditure elasticity

The Engel curve for each good or service, as outlined in Section 3.2, is estimated for the all UK households using cross-section data for 2009. Data for expenditure (£), age of household reference person and OECD-modified equivalisation scale value, are collected from the UK Living Cost and Food Survey (LCFS) database.[19] Expenditure is then divided by the OECD-modified scale value to obtain equivalised expenditure.[20] The expenditure elasticities by quintiles are then estimated using equations 27 and 30. The value of all above variables in 2009 is held fixed over the

---

[18] This includes standing costs plus unit costs for energy carriers.

[19] www.esds.ac.uk/findingData/efsTitles.asp

[20] Equivalised expenditure is expenditure that is adjusted to take account of household size and composition (number of adults and children). 'OECD-modified equivalence scale' assigns a value of 1 to the household head, of 0.5 to each additional adult member and of 0.3 to each child (www.oecd.org/LongAbstract/0,3425,en_2649_33933_35411112_119669_1_1_1,00.html).

projection interval. Detailed results for the Engel curve estimations and estimated expenditure elasticities are presented in section 5.1. in Table 18.

GHG intensity

Estimation of GHG intensities[21] (tCO_2e/£) for each category of expenditure and saving is based on Surrey Environmental Lifestyle Mapping Framework (SELMA). SELMA estimates the GHGs that arise in the production, distribution and consumption of goods and services purchased in the UK from 'consumption perspective' (Druckman and Jackson 2008, 2009a, 2009b). The last year that GHG intensities are available from SELMA is 2004 and these are held fixed over the projection interval for simplicity. The exception applies to GHG intensity of electricity[22] which is estimated for 2009[23] and held fixed as this value. Table 7 in Appendix 2 shows the estimated GHG intensities based on SELMA for different categories. In addition in one scenario, the GHG intensity of electricity is estimated

[21] GHG intensities are calculated dividing the GHG emissions due to household expenditure in each category/investment by the household real expenditure in the same category/ real gross capital formation. Real values (reference year 2009) are calculated based on nominal values and relevant implied deflator data from Office for National Statistics (ONS): www.ons.gov.uk.

[22] This is because the GHG intensity of electricity is expected to fall due to increase use of renewable energy over time.

[23] Total domestic electricity consumption (kWh) in 2009 obtained from DUKES 2011 multiplied by 2009 electricity conversion factor ($kgCO_2e$/kWh) gives total GHG due to domestic electricity consumption ($kgCO_2e$). This is then divided by total household electricity expenditure in 2009 to obtain GHG intensity of electricity (tCO_2e/£).

according to Committee for Climate Change (CCC)[24] target and therefore varies over time.

5. Results

This section first presents the estimated Engel curve for each category of goods and services and the associated expenditure elasticities by household income quintiles. We then present estimates of the rebound effects by income quintiles. Finally we show the difference in rebound effect according to how embodied energy is accounted for.

5.1. Engel curve and expenditure elasticity

The White test for heteroskedasticity shows that heteroskedasticity can not be rejected for all the Engel curve equations either for the WL or DSL functional forms. Therefore, 'White heteroskedasticity-consistent standard errors & covariance' is used for estimation to correct for heteroskedasticity. Table 1 shows the estimation results for the WL and DSL Engel curves for all households.

{Table 1 about here}

For the WL functional form, the coefficients of 'logarithm of equivalised total expenditure' and the 'age of household reference person' are statistically significant for all expenditure categories.[25]

---

[24] According to CCC target the emissions from the power sector need to be reduced by around 40% by 2020 compared to its 1990 level (CCC 2008 pp.200 and www.theccc.org.uk/sectors/power). Using the CCC target, the average annual growth rate over the period 1990-2020 is used to predict GHG intensity for electricity between 2009 and 2020.

[25] The exception applies to the coefficient of 'age of household reference person' for 'miscellaneous goods and services'.

For the DSL functional form, either the coefficient for 'equivalised expenditure for the commodity' or 'equivalised total expenditure' is statistically insignificant.[26] The coefficient of the 'age of household reference person' is statistically significant for all expenditure categories.[27]

In general, WL produces more satisfactory results than DSL in terms of statistical significance of explanatory variables coefficients. However, expenditure elasticities by household quintiles are estimated for both functional forms and used for our rebound estimation for comparison purposes. In general, the expenditure elasticity for each category decreases when moving from the first to the fifth quintile for both WL and DSL functional forms.[28] Table 2 shows the expenditure elasticities for WL and DSL Engel curves by household quintiles respectively.

{Table 2 about here}

In general, the expenditure elasticity for the total sample ('all', which refers to all quintiles) estimation in WL and DSL functional forms are very close, except for

[26] The exception applies to 'food & non-alcoholic beverages', 'other housing' and 'vehicle fuels and lubricants' categories where the coefficients are both statistically significant.

[27] The exception applies to 'alcoholic beverages, tobacco and narcotics' and 'miscellaneous goods and services' categories.

[28] The exception applies to 'vehicle fuels and lubricants' category in WL where the expenditure elasticity increases from the third to the fifth quintile. Similarly, for 'furnishings' and 'recreation and culture' categories in DSL, the expenditure elasticity increases from the first to the fifth quintile and for 'other fuels' category, increases from the third to the fourth quintile.

‘electricity’ and ‘vehicle fuels and lubricants’. However, the individual expenditure elasticities for the quintiles are not necessarily similar for all categories.

5.2. Rebound effects

The estimates of rebound effects from the different measures are averaged over a period of ten years from 2009 to 2018. It is assumed that energy efficiency measure or abatement action are applied in 2009 and the cost saving due to them begin from this year. For simplicity, all variables are held fixed over the 10 year projection period.

Rebound results are estimated under five different assumptions for each of the household income quintiles:

a) re-spending effects only, ignoring capital costs anf embodied GHGs;

b) re-spending and embodied effects, ignoring capital costs;

c) re-spending and embodied effects, allowing for unsubsidised capital costs;

d) re-spending and embodied effects, allowing for subsidised capital costs;

e) re-spending and embodied effects, allowing for subsidised capital costs and CCC the GHG intensity according to the reduction target in power sector.

Figure 1 illustrates the estimated rebound effect for above assumptions using WL and DSL Engel curve functional forms by household quintile for the rebound definition in equation 12. In general, the results using both WL and DSL functional forms are similar, with WL giving relatively smaller estimates for rebound. The estimated rebound under assumption ‘a’, for home energy efficiency measures[29] are between 12% for the highest to 22% for the lowest income quintiles with an average of about

[29] This includes measure numbers 1 to 9 in Appendix: Table 2.

14% for all households. The difference between the estimated rebound effects for 'lighting'[30,31] and 'heating'[32] measures is relatively small since GHG intensity of 'electricity' and 'gas', as a major source for heating, are very close. In addition, the results are moderate because 'electricity' and 'gas' have relatively high GHG intensities, therefore the expected reduction in GHGs due to these measures are relatively much higher than the re-spending effect including re-spend of the avoided expenditure in other categories with lower GHG intensities .

The rebound effects for 'efficient car' and the 'food waste reduction' and 'car use reduction' abatement actions [33] are estimated to be higher than other measures. This is because 'vehicle fuels' and 'food' have relatively lower GHG intensities compared to some other categories that the avoided expenditure is being re-spent. Therefore, the difference between the re-spending effect and expected reduction in GHGs due to these measures are relatively smaller than other measures .The estimated rebound effects for these measures are between 28% for the highest to 106% (backfire) for the lowest income quintiles with an average of 33% to 74% for all households, among them 'food' having the highest rebound. In general, the results show that rebound effects are higher for lower income groups; hence a negative relationship between rebound and income. The reason for this is the generally higher expenditure elasticity

[30] This includes measures numbers 5 and 6 in Appendix: Table 2.

[31] The estimated rebound effects for 'lighting' measures are influenced by modelling of the heat replacement effect (i.e. the increased use of heating fuels to compensate for the loss of heat from GLS bulbs).

[32] This includes measures numbers 1, 2, 3, 4 and 7 in Appendix: Table 2.

[33] This includes measure numbers 11, 12 and 13 in Appendix: Table 2.

for different categories of commodities as well as higher share of energy and food expenditure for lower income households.

Adding embodied effect to assumption 'a' increase the rebound effect. The estimated rebound effects under assumption 'b', for home energy efficiency measures are between 12% for the highest to 85% for the lowest income quintiles with an average of about 22% for all households. The rebound results for most measures are moderate; the exception being 'solar thermal' and 'loft insulation' with the former having a double rebound than the later. Embodied effect is assumed to be equal for all household quintiles and adding this effect to re-spending effect increases the estimated rebound for all household groups, but this increase is larger for lower income groups. This means lower income households are more sensitive to embodied effect than higher income households. The results indicate that embodied effect could be important in estimating the rebound effect; hence ignoring it might result in rebound being underestimated. As there is no embodied effect associated with 'efficient car' and abatement actions, the estimated rebound for these are the same as in assumption 'a'.

If unsubsidised capital cost is added to assumption 'b' the net cost saving of the measure (re-spending effect) and therefore the rebound effect will decrease. The estimated rebound effects under assumption 'c', for home energy efficiency measures are between -146% and 26% for different income quintiles with an average of about 1% for all households. As the capital cost of 'solar thermal' is relatively high, the rebound results for this measure are highly negative for all income groups. In this case, the reduction in GHGs is more than what expected by engineering effect. The rebound effects for ‘LED lighting’ measures and ‘loft insulation’ (for lower income groups) are also negative but relatively higher than ‘solar thermal’ rebound. For the above mentioned measures (‘solar thermal’, ‘LED lighting’ and ‘loft insulation’), rebound increases for higher income groups as the net cost saving is less negative or even positive for these groups. For all other measures, the rebound effects are generally lower for higher income groups. Capital cost is assumed to be equal for all household quintiles, so the net cost saving decrease is larger for lower income groups. Hence, the larger decrease in re-spending effect for lower income groups decreases the estimated rebound for these groups more than higher income households. The results show that ignoring the capital cost of the measure might result in rebound being overestimated. Again, there is no capital cost associated with abatement actions and as assumed for ‘efficient car’; hence the estimated rebound for these is the same as in assumption ‘a’.

When government subsidy is applied to the capital cost in assumption ‘c’, the net cost saving of the measure and therefore the rebound effect will increase. The estimated rebound effects under assumption ‘d’, for home energy efficiency measures are between 1% and 34% for different income groups with an average of about 15% for all households. The rebound estimates are almost moderate for all measures except for ‘loft insulation’; having at least 24% (for the highest income quintile) rebound among the household quintiles. For all measures, except ‘solar thermal’ and ‘LED EU directive’, the rebound effect generally decreases with higher income. The subsidy for each measure is assumed to be equal for all household quintiles and increases the estimated rebound for all household groups in assumption ‘d’ compared to assumption ‘c’, but this increase is larger for lower income groups. This means lower income households are more sensitive to subsidy for capital cost than higher income households.

Finally, the CCC target for GHG intensity of 'electricity' is used in assumption 'd'. The changes to GHG intensity of 'electricity' will reduce the engineering effect of GHG savings from lighting measures, while having a smaller impact on the GHG emissions from re-spending. As a result, the estimated rebound effects for lighting measures in assumption 'e' are slightly higher than the estimates in assumption 'd'. Here, rebound is between 4% and 29% for different income groups with an average of about 13% for all households.[34] Other explanations are similar to assumption 'd'.

{Figure 1 about here}

Figure 2 presents the estimated rebound effects using the rebound definition in equation 13 with similar assumptions to Figure 1. The results show a similar pattern to the ones in Figure 1, however the estimated rebounds are lower as the embodied effect now reduces the magnitude of rebound.

{Figure 2 about here}

6. Discussion and Conclusion

This paper estimates the combined direct and indirect GHGs rebound effects for a number of energy efficiency improvements and abatement actions for UK households. The variation of rebound effects between household income groups is explored, and

[34] For simplicity, it is assumed that the shift to lower GHG intensity for electricity in the UK (CCC target), would not affect the GHG intensity of other commodities.

the importance of the capital cost and embodied GHGs of the relevant measure in estimating the rebound is investigated.

To do this, the GHGs and cost savings from the different measures are estimated using an engineering model for English dwellings. The GHGs rebound effect due to re-spending of cost savings on different commodities are then estimated and averaged over a 10 year period (2009 to 2018). The calculations combine estimates of the expenditure elasticity and the GHG intensity of different categories of household goods and services. The expenditure elasticities are obtained from the estimated Engel curves using 2009 household cross-section data for the UK.

The results show that the magnitude of the rebound effect varies widely according to the actions taken, depending upon the cost of implementing the measure and the embodied GHGs involved. The estimated rebound increase when embodied effect is added regardless of how the embodied effect is defined in rebound estimation formula. However, estimated rebound for all assumptions when embodied effect is subtracted from potential GHGs saving is lower than when embodied effect is added to the re-spending effect.

Rebound effects tend to be relatively moderate for measures to improve home energy efficiency. The primary reason that the estimated effects are small is that energy consumption is much higher GHG intensive than other goods and services. The exception is for ‘solar thermal’ and ‘loft insulation’ were rebound is found to be relatively high when capital costs are ignored; owing to the substantial embodied GHGs associated with these measures. Estimated rebound is significantly larger for measures relevant to transport and reduce food waste. This difference results from the lower GHG intensity of expenditure on ‘vehicle fuels’ and ‘food’ relative to expenditure on ‘gas’ or ‘electricity’. In general, the rebound effects are smaller when capital cost is unsubsidized for energy efficiency improvements at homes. On the other hand, abatement actions have high rebound effects as they are not associated with any cost and embodied effect.

Rebound effects tend to be generally higher for lower income groups, due to the relatively high proportion of their expenditure on gas and electricity in addition to relatively higher expenditure elasticities. In fact, lower income groups do not have the living standards. Therefore, they might have higher rebound because they are trying to achieve the living standards such as thermal comfort at home. Any effort to reduce the rebound for low income groups might lower their standard of living again. Although, the rebound is smaller when the capital cost is unsubsidised, hence closer to the GHGs reduction target, but eliminating the subsidies might bring back fuel poverty and lower standard of living for low income groups. Therefore, the higher rebound for low income households should not be regarded as a problem.

In addition, for the energy efficiency measures with negative (resulting in negative rebound) or very low net cost saving i.e. ‘loft insulation’ (especially for lower income quintiles), ‘LED lighting’ and ‘solar thermal’, eliminating the subsidies could discourage any household income group to apply such energy efficiency improvements in their dwellings. Therefore, the above three measures are possibly the ones that subsidy could best be aimed for all income groups. As the estimated rebound for all of the energy efficiency measures (including the above three measures) with subsidy is lower than 100% for all household quintiles, it is still worthwhile to apply the measures even when capital cost is subsidised.

Overall, the results demonstrate the importance of taking account of rebound effects when estimating the impact of energy efficiency and abatement actions. However, there are some limitations to this study. Although we have used the appropriate available expenditure for each income quintile, we do not have information about which type of house they are likely to live in within the model. The assumptions about energy efficiency improvement measures and abatement actions are only available for average household and not by household income quintiles.

Finally, the approach used in this paper does not capture substitution effects but focuses on income effects only. Adding the substitution effects might affect the size of the estimated rebound effects. This issue is the focus of the ongoing work.

Acknowledgments

This research was supported by funding from the UK Department of Environment Food and Rural Affairs (DEFRA), the UK Economic and Social Research Council and the Scottish Government as part of the Sustainable Lifestyles Research Group (SLRG).

References

Chitnis, M., Hunt, L. C., 2010. Contribution of economic versus non-economic drivers of UK household expenditure, RESOLVE Working Paper series, 03-10, University of Surrey.

Chitnis, M., Hunt, L. C., 2011. Modelling UK household expenditure: economic versus non-economic drivers, *Applied Economics Letters*, 18 (8), 753-767.

Chitnis M., Sorrell S., Druckman A., Firth S., and Jackson T., 2012. Estimating direct and indirect rebound effects for UK households, SLRG Working Paper Series, 01-12, University of Surrey.

DECC, Extending the Carbon Emissions Reduction Target to December 2012 - Impact Assessment; Department of Energy and Climate Change: London, 2010.

DECC, Quarterly Energy Prices, December 2011.

CCC, 2008, Building a low-carbon economy – the UK's contribution to tackling climate change, December.

Druckman, A.; Jackson, T. The Surrey Environmental Lifestyle MApping (SELMA) framework: development and key results to date; RESOLVE Working Paper Series 08-08, University of Surrey, 2008.

Druckman, A.; Jackson, T., 2009a. The carbon footprint of UK households 1990-2004: a socio-economically disaggregated, quasi-multiregional input-output model. *Ecological Economics,* 68, 2066–2077.

Druckman, A.; Jackson, T. Mapping our carbon responsibilities: more key results from the Surrey Environmental Lifestyle MApping (SELMA) framework; RESOLVE Working Paper Series 02-09, University of Surrey, 2009b.

Druckman, A., Chitnis, M., Sorrell, S., Jackson, T., 2011. Missing carbon reductions? Exploring rebound and backfire effects in UK households. *Energy Policy*, 39, 3572–3581.

Firth, S. K.; Lomas, K. J.; Wright, A. J., Targeting household energy-efficiency measures using sensitivity analysis. *Building Research & Information,* 2009, 38, 25-41.

Haque, M. Ohidul. 2005. Income elasticity and economic development: Methods and applications. Dordrecht: Springer.

HM Government, 2008. Climate Change Act 2008. London, UK, The Stationery Office Limited.

Jackson, T., 2011. Confronting consumption: challenges for economics and for policy. In S Dietz, J Michie and C Oughton (Eds), The Political Economy of the Environment: an Interdisciplinary approach, 189-212. Abingdon and New York: Routledge.

Murray, C. K., 2011. Income dependent direct and indirect rebound effects from 'green' consumption choices in Australia, MPRA Paper No. 34973.

Sorrell, S., 2010. Mapping rebound effects from sustainable behaviours: key concepts and literature review. Sussex Energy Group, SPRU, University of Sussex, Brighton.

Thomas, A. and Azevedo, I., 2012. Direct and Indirect Rebound Effects for the U.S. Household Using a Partial Equilibrium Model, Center for Climate and Energy Decision Making Working Paper, Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA.

WRAP, The food we waste. Banbury, Oxon, Waste and Resources Action Programme, 2008.

Table 1: Engel curve estimation results for whole sample in 2009

Category \ Functional form	WL				DSL				
	α_i	β_i	γ_i	$\overline{R}^2$	λ_i	θ_i	φ_i	ρ_i	$\overline{R}^2$
Food & non-alcoholic beverages	0.57 (41.84)	-0.09 (-36.78)	0.0009 (13.89)	0.32	-59.19 (-20.48)	-0.01 (-4.42)	16.17 (25.86)	0.18 (15.27)	0.22
Alcoholic beverages, tobacco & narcotics	0.11 (12.33)	-0.01 (-8.64)	-0.0001 (-3.10)	0.02	-13.84 (-6.27)	0.0002 (0.10)*	4.04 (8.40)	-0.004 (-0.54)*	0.04
Clothing & footwear	-0.01 (-1.58)*	0.02 (11.47)	-0.0004 (-7.72)	0.04	-43.30 (-4.89)	0.01 (1.48)*	10.68 (5.18)	-0.07 (-5.29)	0.18
Electricity	0.16 (24.66)	-0.03 (-23.45)	0.0003 (10.57)	0.23	-4.72 (-4.81)	-0.0001 (-0.12)*	1.69 (8.14)	0.05 (12.26)	0.06
Gas	0.12 (18.61)	-0.02 (-17.60)	0.0004 (10.77)	0.13	-7.45 (-7.58)	-0.0004 (-0.60)*	1.99 (10.38)	0.06 (11.77)	0.05
Other fuels	0.01 (1.52)*	-0.001 (-1.94)	0.0002 (5.97)	0.01	-6.36 (-6.40)	-0.0007 (-1.35)*	1.21 (6.81)	0.03 (5.43)	0.01
Other housing	0.33 (17.64)	-0.03 (-10.43)	-0.001 (-9.83)	0.03	-4.45 (-0.42)*	0.03 (2.21)	6.94 (2.78)	-0.32 (-11.38)	0.09
Furnishings	-0.12 (-8.07)	0.03 (11.39)	0.0006 (7.15)	0.04	144.12 (1.31)*	0.28 (2.31)	-37.81 (-1.46)*	0.16 (4.85)	0.34
Health	-0.04 (-6.23)	0.01 (6.47)	0.0003 (7.68)	0.02	-18.60 (-3.06)	0.01 (1.11)*	2.89 (1.87)	0.09 (4.72)	0.04
Vehicle fuels & lubricants	0.02 (2.97)	0.01 (6.39)	-0.0002 (-3.88)	0.01	-45.15 (-19.78)	-0.01 (-2.82)	11.34 (22.59)	-0.03 (-3.40)	0.20
Other transport	-0.17 (-11.16)	0.05 (19.90)	-0.0005 (-5.50)	0.09	-96.02 (-3.12)	0.05 (1.54)*	21.11 (2.92)	-0.08 (-3.00)	0.23
Communication	0.14 (25.24)	-0.02 (-20.98)	-0.0001 (-2.15)	0.12	-7.54 (-7.11)	-0.00001 (-0.02)*	2.98 (13.72)	-0.02 (-4.33)	0.10
Recreation & culture	-0.12 (-6.31)	0.04 (12.91)	0.0005 (5.82)	0.04	180.53 (1.39)*	0.42 (2.94)	-47.60 (-1.56)*	0.17 (4.24)	0.46
Education	-0.05 (-7.09)	0.01 (8.61)	-0.0002 (-5.12)	0.03	1.70 (0.37)*	0.03 (10.14)	-0.44 (-0.46)*	-0.08 (-4.04)	0.06
Restaurants and hotels	-0.003 (-0.21)*	0.02 (10.79)	-0.0005 (-7.42)	0.04	0.56 (0.02)*	0.11 (2.87)	0.47 (0.06)*	-0.11 (-5.13)	0.28
Miscellaneous goods & services	0.04 (3.68)	0.01 (3.91)	-0.00001 (-0.11)*	0.004	-20.30 (-0.82)*	0.08 (2.75)	4.33 (0.73)*	-0.01 (-0.26)*	0.22

Notes:

- t-statistic is shown in parenthesis.
- $\overline{R}^2$ is the adjusted coefficient of determination.
- * denotes that t-test could not be rejected at 10 probability level.
- All variables values are in nominal terms.

Table 2: Expenditure elasticities by quintiles in 2009

Category \ Quintile	WL						DSL					
	1	2	3	4	5	All	1	2	3	4	5	All
Food & non-alcoholic beverages	0.65	0.57	0.48	0.38	0.06	0.39	0.70	0.48	0.41	0.41	0.24	0.40
Alcoholic beverages & tobacco	0.71	0.68	0.65	0.60	0.45	0.59	1.03	0.68	0.56	0.56	0.38	0.56
Clothing & footwear	1.51	1.34	1.32	1.27	1.28	1.30	4.22	1.80	1.35	1.23	0.64	1.11
Electricity	0.57	0.37	0.17	0.00	-0.62	0.05	0.31	0.26	0.26	0.25	0.21	0.25
Gas	0.62	0.49	0.34	0.15	-0.25	0.23	0.42	0.33	0.32	0.32	0.24	0.31
Other fuels	0.85	0.77	0.82	0.79	0.69	0.77	1.35	1.16	0.66	0.72	0.39	0.69
Other housing	0.73	0.73	0.68	0.68	0.56	0.66	0.90	0.63	0.62	0.58	0.58	0.61
Furnishings	1.60	1.56	1.44	1.40	1.30	1.38	-3.01	0.48	1.39	1.47	2.06	1.55
Health	1.82	1.69	1.59	1.50	1.38	1.48	4.78	2.78	1.99	1.86	0.83	1.47
Vehicle fuels & lubricants	1.20	1.13	1.12	1.13	1.17	1.14	3.24	1.26	0.85	0.85	0.41	0.83
Other transport	2.31	1.80	1.61	1.52	1.40	1.52	7.28	2.97	1.85	1.78	0.75	1.41
Communication	0.63	0.54	0.47	0.39	0.06	0.38	0.64	0.48	0.41	0.41	0.31	0.41
Recreation & culture	1.39	1.37	1.31	1.30	1.23	1.28	-1.04	0.84	1.30	1.39	1.71	1.41
Education	9.96	5.63	3.97	2.37	1.47	1.90	20.61	11.38	7.47	5.27	1.22	2.28
Restaurants & hotels	1.34	1.27	1.24	1.22	1.22	1.23	1.70	1.36	1.18	1.16	1.06	1.15
Miscellaneous goods & services	1.10	1.10	1.10	1.09	1.09	1.09	1.55	1.31	1.17	1.16	0.95	1.10

Note:
- All values are rounded to two decimals.
- All variables values are in nominal terms.

Figure 1: Rebound effect using definition 'R'

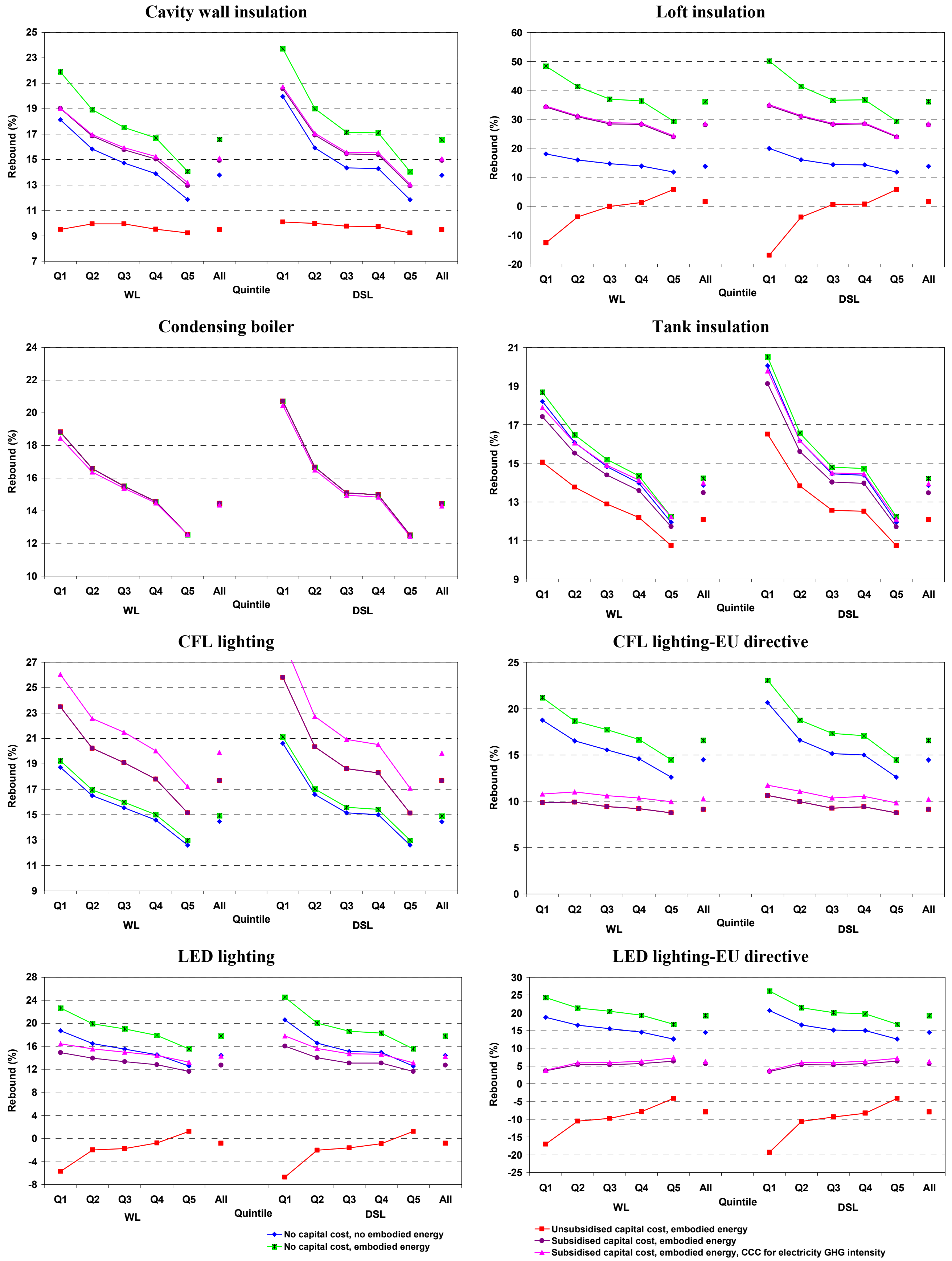


Figure 1: Continued.

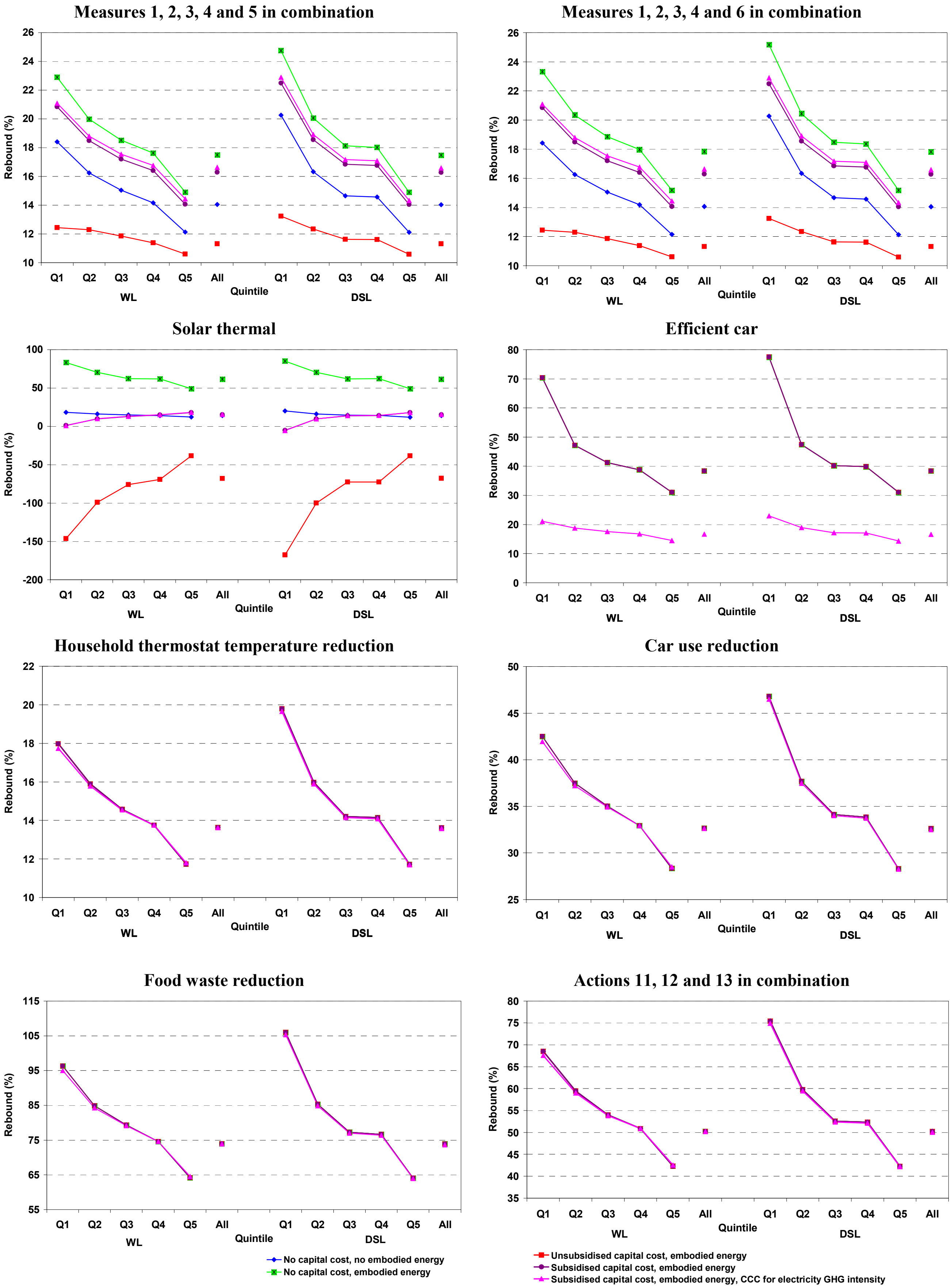


Figure 2: Rebound effect using definition ‘R′’

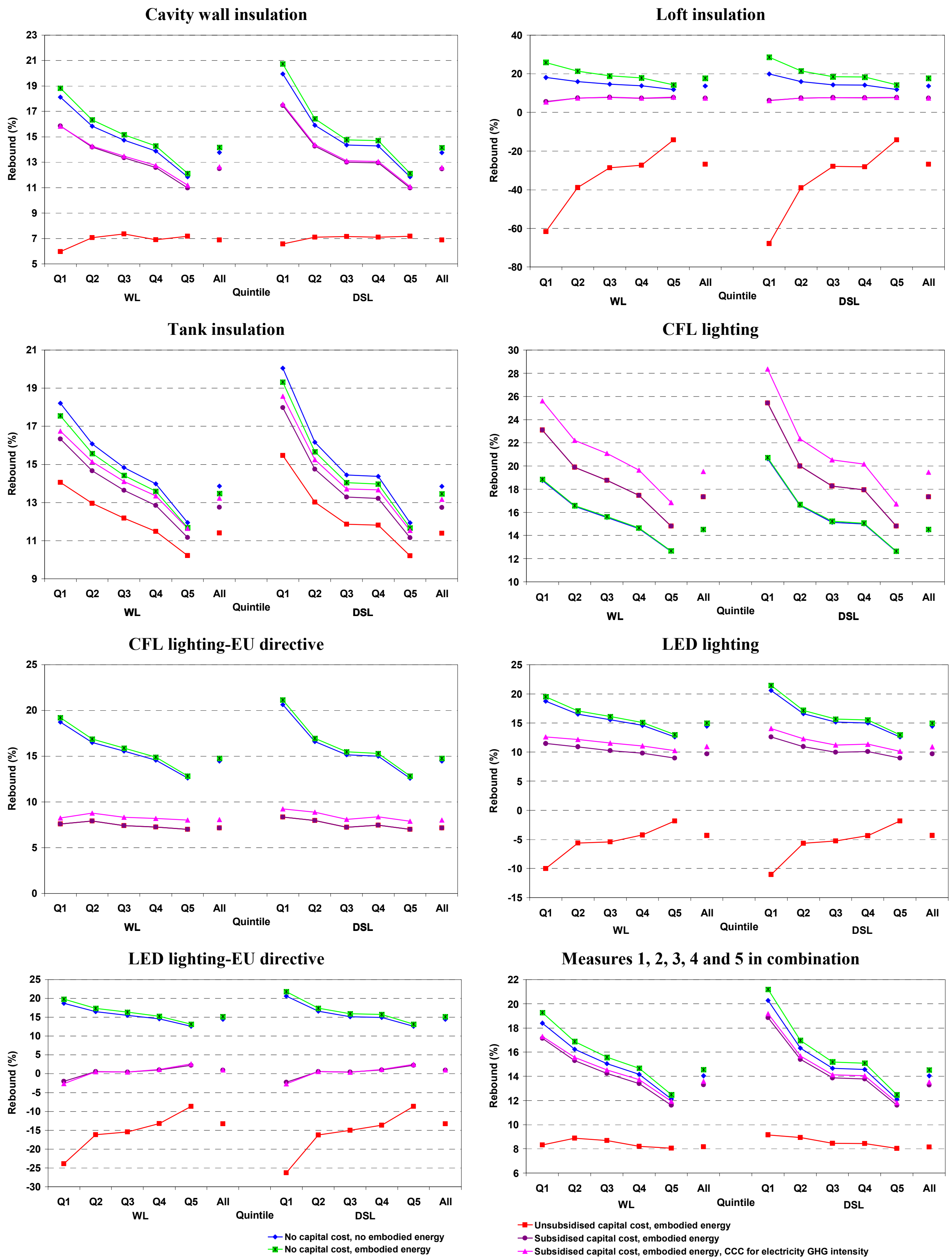
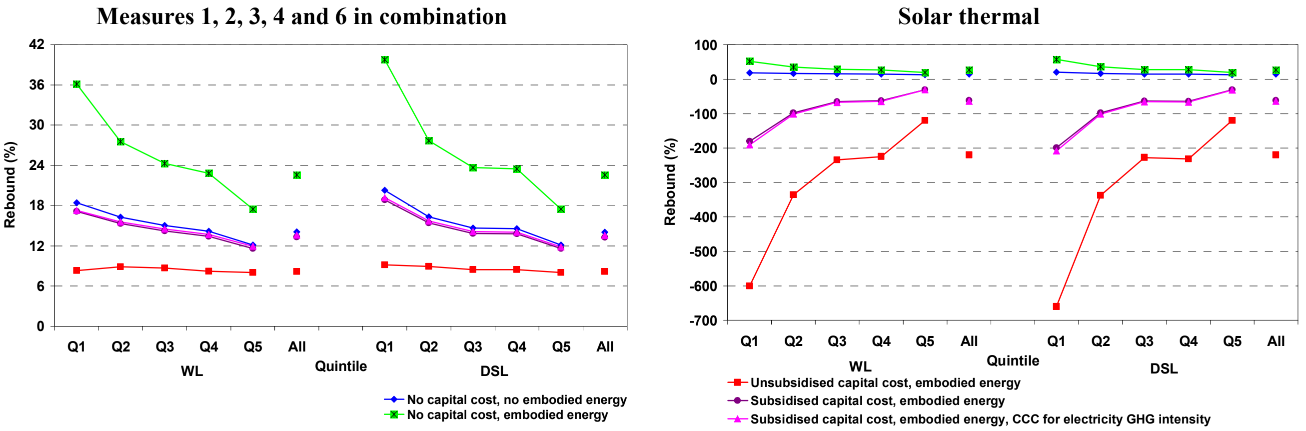


Figure 2: Continued.



Appendix 1:

For the engineering effects due to replacement of inefficient car by efficient car, some assumptions are made for these two types of cars. According to the data available for Great Britain (GB) from Department for Transportation (DFT)[35], the most licensed car in the UK is Ford Focus, the average engine capacity for diesel cars in 2010 is 2002cc, the average fuel consumption for new diesel cars in 2009 is 5.7 litre/100km and the ratio of car[36] ownership per household in 2008/2009 is 1.4. The assumptions for the inefficient car are based on above information: the number of cars per household is assumed to be one and the car model representing an inefficient diesel car is assumed to be Ford Focus 2.0 Duratorq TDCi 136PS 3/5dr Saloon with engine capacity of 1997cc and fuel consumption of 5.5 litre/100km.[37] An alternative efficient diesel car is assumed to be AUDI A3 1.6 TDI 105PS start-stop with engine capacity of 1598cc and fuel consumption of 3.8 litre/100km.[38] The assumptions for both cars are given in Appendix 2: Table 1. Annual change in emissions due to increased efficiency for all cars is then calculated using the annual average car mileage and the ratio of diesel cars to total cars.

For food abatement action, the broad finding that an average UK household throws away one third of the food purchased is used (WRAP 2008). Therefore, a reduction in ‘food and non-alcoholic beverages’ expenditure is assumed to be 33% with a corresponding reduction of 33% in its’ associated GHG emissions.

[35] www.dft.gov.ukpdate

[36] Includes vans.

[37] www.nextgreencar.com/view-car/5488/FORD-Focus-Diesel-Manual-6-speed

[38] www.nextgreencar.com/view-car/28355/AUDI-A3-Diesel-Manual-5-speed

For the travel abatement action (walking or cycling instead of using a car for trips of less than 2 miles), based on data from DFT[39] for 2009 it is estimated that this action would reduce expenditure on 'vehicle fuels', as well as its associated GHG emissions by 22%.

[39] www.dft.gov.uk/statistics/releases/national-travel-survey-2009. See National Travel Survey 2009 and XLS tables: Table NTS308 Average number of trips by trip length and main mode: Great Britain.

Appendix 2:

Table 1: Assumptions for efficient car measure

	Inefficient car	Efficient car	GB
CO2 emission (g/km)	144	99	-
Annual average (petrol & diesel) car mileage in 2009	-	-	8429
Ratio of diesel cars to total cars in 2010 (%)	-	-	29

Table 2: Percentage change in estimated GHG[1] from the different measures for an 'average' household[2]

No.	Measure	Gas	Electricity	Other fuels	Vehicle fuels	Food
1	Cavity wall insulation	-8.8	-1.7	-7.2	-	-
2	Loft insulation	-2.2	-0.5	-2.3	-	-
3	Condensing boiler	-11.8	0.6	-0.1	-	-
4	Tank insulation	-1.8	-1.6	-1.9	-	-
5	CFLs	0.9	-4.5	0.9	-	-
6	LEDs	1.1	-5.4	1.0	-	-
7	Solar thermal	-3.6	-0.9	-4.9	-	-
8	1,2,3,4 and 5	-22.4	-7.6	-10.6	-	-
9	1,2,3,4 and 6	-22.2	-8.5	-10.4	-	-
10	Efficient car	-	-	-	-31.0	-
11	Household thermostat temperature reduction	-9.4	-2.0	-10.5	-	-
12	Car use reduction	-	-	-	-22.0	-
13	Food waste reduction	-	-	-	-	-33.0
14	11, 12 and 13	-9.4	-2.0	-10.5	-22.0	-33.0

1. Emissions include both direct emissions from fuel combustion and indirect emissions from different stages of the fuel cycle.
2. Measures 1 to 9 relate to average English dwelling and measures 10 to 14 relate to average UK household.

Table 3: Assumptions for the embodied GHGs associated with each measure for an average household for a ten year period

No.	Measure	embodied GHGs for an average dwelling (kg CO_2e)
1	Cavity wall insulation	55.2
2	Loft insulation	118.3
3	Condensing boiler	0
4	Tank insulation	2.3
5	CFLs	12.7 (2.6)[1]
6	LEDs	34.6 (24.5)[1]
7	Solar thermal	427
8	1,2,3,4 and 5	178.4
9	1,2,3,4 and 6	200.3
10	Efficient car	0
11	Household thermostat temperature reduction	0
12	Car use reduction	0
13	Food waste reduction	0
14	11, 12 and 13	0

1. Estimates in brackets are *without* allowing for the EU ban on incandescent bulbs.

Table 4: Assumptions for the cost of efficient and inefficient cars in 2009

	Inefficient car[1]	Efficient car[2]	UK
Litre/100km	5.5	3.8	-
Tax (£)	125	0	-
Diesel price pence per litre[3]	-	-	104

1. www.nextgreencar.com/view-car/5488/FORD-Focus-Diesel-Manual-6-speed
2. www.nextgreencar.com/view-car/28355/AUDI-A3-Diesel-Manual-5-speed
3. DECC 2011.

Table 5: Estimated percentage change in annual expenditure from the different measures for an 'average' household[1]

No.	Measure	Gas	Electricity	Other fuels	Vehicle fuels	Food
1	Cavity wall insulation	-7.7	-1.5	-7.1	-	-
2	Loft insulation	-1.9	-0.4	-2.3	-	-
3	Condensing boiler	-10.3	0.6	-0.1	-	-
4	Tank insulation	-1.5	-1.5	-1.8	-	-
5	CFLs	0.8	-4.1	0.8	-	-
6	LEDs	1.0	-5.0	1.0	-	-
7	Solar thermal	-3.6	-0.8	-4.7	-	-
8	1,2,3,4 and 5	-19.4	-7.0	-10.5	-	-
9	1,2,3,4 and 6	-19.3	-7.8	-10.4	-	-
10	Efficient car[2]	-	-	-	-31.0	-
11	Household thermostat temperature reduction	-12.0	-2.0	-14.0	-	-
12	Car use reduction	-	-	-	-22.0	-
13	Food waste reduction	-	-	-	-	-33.0
14	11, 12 and 13	-12.0	-2.0	-14.0	-22.0	-33.0

1. Measures 1 to 9 relate to average English dwelling and measures 10 to 14 relate to average UK household.
2. Cost saving due to efficiency only. It does not include tax saving.

Table 6: Assumptions for the capital cost associated with each measure for an 'average' household, averaged over a ten year period

No.	Measure	capital cost without subsidy (£)	capital cost with subsidy (£)
1	Cavity wall insulation	179	41
2	Loft insulation	235	54
3	Condensing boiler	0	0
4	Tank insulation	17.50	6.3
5	CFLs[1]	57.6 (-21.6)	57.6 (-21.6)
6	LEDs[1]	254.4 (175.2)	127.2 (48)
7	Solar thermal	1489	532
8	1,2,3,4 and 5	409.9	79.7
9	1,2,3,4 and 6	256.3	53.3
10	Efficient car	0	0
11	Household thermostat temperature reduction	0	0
12	Car use reduction	0	0
13	Food waste reduction	0	0
14	11, 12 and 13	0	0

1. Estimates in brackets for energy efficient lighting are *without* allowing for the EU ban on incandescent bulbs.

Table 7: Estimated GHG intensities in 2004

No.	COICOP[1] category	Description	GHG intensity[2] (tCO_2e/£)
1	1	Food & non-alcoholic beverages	0.0011
2	2	Alcoholic beverages, tobacco, narcotics	0.0002
3	3	Clothing & footwear	0.0005
4	4.5.1	Electricity[3]	0.0050
5	4.5.2	Gas	0.0047
6	4.5.3 and 4.5.4	Other fuels	0.0069
7	4.1 to 4.4	Other housing[4]	0.0002
8	5	Furnishings, household equipment & routine household maintenance	0.0007
9	6	Health	0.0003
10	7.2.2.2	Vehicle fuels and lubricants	0.0024
11	Rest of 7	Other transport	0.0012
12	8	Communication	0.0004
13	9	Recreation & culture	0.0006
14	10	Education	0.0002
15	11	Restaurants & hotels	0.0005
16	12	Miscellaneous goods & services	0.0005
17	_	Investment	0.0006

1. Classification of Individual Consumption According to Purpose
2. The reference year for 'real' expenditure used to obtain GHG intensity is 2009.
3. The GHG intensity of 'electricity' is for 2009.
4. 'Other housing' includes rent, mortgage payments, maintenance, repair and water supply.