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Indirect rebound involving embodied energy use re-spending decisions:
How do we treat negative multiplier effects in energy supply chains?

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Indirect rebound involving embodied energy use in re-spending decisions: how do we treat negative multiplier effects in energy supply chains?[1]

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Abstract: A growing area of research into rebound effects from increased energy efficiency involves the application of demand-driven input-output models to consider indirect rebound associated with re-spending decisions by households with reduced energy spending requirements. However, there is often a lack of clarity in applied studies as to how indirect rebound effects involving energy use embodied in supply chains have been calculated. We focus on a theoretical debate regarding the treatment of reduced energy requirements by energy producers and their up-stream supply chains as energy spending decreases with improved efficiency. We show that both the magnitude and direction of embodied energy rebound effects are highly sensitive to what is assumed to be part of potential energy savings, which we argue should be considered in terms of energy savings *anticipated* by decision makers. We also extend the focus of most studies of rebound effects via embodied energy impacts to consider impacts on energy use and CO_2 emissions embedded in international supply chains and consider how these are reflected in alternative definitions of rebound.

1. Introduction

An interesting area of rebound research has developed in considering the embodied energy effects of the re-spending decisions that households make when they realise savings from reduced expenditure on energy as their efficiency increases. Borenstein (2015) argues that there is potential for net negative rebound effects to occur even at the microeconomic level of a *net* direct rebound that includes consideration of a substitution effect and consumers re-allocate spending from more to less energy-intensive goods or services. Consideration of the latter would seem to require estimation of energy use in supply chains of energy and non-energy

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goods. However, as argued in Turner (2013) there are issues in terms of a lack of consistent terminology used for different elements of rebound effects. Nonetheless, there is some common ground in how researchers have considered the impact of spending decisions on energy use embodied in the supply chains of different goods and services (generally but not exclusively – e.g. Borenstein (2105) – classed as a form of indirect rebound effects). This is in the application of the simplest economy-wide modelling framework, demand-driven input-output (IO) models. These models may strictly be considered partial equilibrium, given that they abstract from any changes in prices and nominal incomes (Lecca et al., 2014). Moreover, with assumptions of universal Leontief technology, they are not ideal for modelling impacts of changes in technology or efficiency.[2] Nonetheless, they offer an insight into rebound impacts from changes in energy use across the production side of the economy that is purely in response to a change in the pattern of household expenditure that may follow an efficiency improvement. That is, before any price effects come into play.

There seems no dispute in the growing literature on IO analysis of embodied energy effects that, alongside increased energy embodied in supply chains of goods/services that spend is redirected towards, there will be decreases in energy embodied in energy supply. The latter includes energy directly used by an energy carrier affected by an efficiency improvement (e.g. gas used in electricity generation when efficiency in electricity use increases) and in energy use embodied in supply chains supporting that carrier (e.g. in extracting and supplying gas to the generation plant). However, there is debate over how this should be treated in calculating rebound. The key analytical contribution is that of Guerra and Sancho (2010). They argue that any reduction in energy directly used or embodied in the supply chain of an energy type/carrier (such as electricity, coal, gas, or petrol/diesel) as demand falls with improved energy efficiency should be treated as part of the ‘potential energy saving’ that rebound estimates are scaled against. That is, as we move from the individual to economy-wide level in considering actual energy savings, we should similarly extend our perspective on potential energy savings.

Turner (2013) disputes this argument. She proposes that practical considerations for policymakers who need to interpret rebound as an indicator in assessing the net impacts on energy use in the wider economy should outweigh issues of strict general equilibrium definitions put forward by Guerra and Sancho. That is, the Turner argument is that rebound is something that we use economy-wide models to quantify, rather than being a general equilibrium concept in itself. In this paper we assess this debate in the context of practical applications of IO multiplier methodology, considering findings for rebound for simple numerical examples using data for the UK and alternative treatments argued by Guerra/Sancho and Turner. Moreover, given the increasingly international nature of supply chain activity, we extend consideration of

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[2] For this reason more flexible (and theory consistent) computable general equilibrium (CGE) models, which incorporate input-output databases, are more commonly employed to assess economy-wide impacts of increased energy efficiency, including fuller assessment of ‘economy-wide rebound’ (Turner, 2013).

changes in embodied energy and rebound to consider impacts on global energy use as distinct from impacts within the UK itself (i.e. extending from a territorial/production accounting focus to a consumption accounting perspective).

The remainder of the paper is structured as follows. In Section 2, we review in more detail the debate over estimation of potential energy savings in rebound calculations that involve consideration of energy embodied in reduced energy supply activity. In Section 3, we present the IO method used to decompose multiplier calculations that underlie indirect rebound estimates. In Section 4, we apply this method to a series of simple 'what if' scenarios of re-spending by UK households following an efficiency improvement in their use of electricity and gas. Conclusions are drawn in Section 5.

2. The debate: treatment of negative multiplier effects in energy supply

'Multiplier analysis' using the demand-driven IO model is ideal for examining energy and/or pollution embodied throughout industrial supply-chains.[3] Three examples of studies that employ demand-drive IO to consider indirect 're-spending' rebound effects (Sorrell, 2009) are found in Druckman *et al*. (2011), Freire-Gonzàles (2011) and Thomas and Azevedo (2013a,b) for UK, Spanish (Catalonia) and US case studies respectively. These studies find that rebound from energy use embodied in re-spending decisions may be large, depending on the specific scenario modelled.

However, it is crucial to identify that as well as increased embodied energy requirements of the consumption goods that households may reallocate their expenditure in favour of, where rebound in direct energy use by more efficient households energy use is less than 100% (i.e. a net decrease), there will also be reduced embodied energy requirements from energy-savings. All goods and services will have some embodied energy requirement (from the perspective of the final consumer) both through energy directly used in the production of the good/service in question and in the production of (both energy and non-energy) intermediate inputs at different stages in energy and non-energy supply chains.

Thus, just as increased consumption of non-energy goods and services involves increased embodied energy requirements down their supply chains (positive multiplier effects), reduced consumption of energy involves decreased embodied energy requirements as less energy and non-energy inputs are required in the supply chains of energy producers (negative multiplier effects). Moreover, energy production (for example, electricity generation in gas- or coal-fired plants) tends to be energy-intensive both on site of production (the generation plant) and in the

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[3] See Miller and Blair (2009) for IO modelling methods more generally, and Turner et al. (2007), for the inter-regional IO multiplier method that is also commonly employed in consumption-based environmental 'footprint' studies, and which we extend in the next section for the applied work in Section 4.

supply chain serving this production (e.g. in gas or coal extraction). On this basis, there is a strong chance that redirected spending away from the energy-intensive outputs of energy supply sectors in favour of less (directly and indirectly) energy-intensive non-energy goods and service will lead to a net negative impact on overall energy use beyond that of the user whose efficiency has increased. This will be captured by IO models as long as a full set of expenditure changes (both positive and negative) are introduced.

Turner (2009) considers this issue for the case of increased efficiency in industrial energy use in a computable general equilibrium (CGE) modelling context (incorporating an IO database), identifying negative multiplier effects in energy supply chains as one potential source of negative results for total rebound. Lecca *et al*. (2014) finds that negative multiplier effects in energy supply are sufficient to result in a net negative re-spending rebound effect from increased efficiency in UK household energy use, but not sufficient to realise negative rebound at the full economy-wide level. Most studies of rebound effects associated with changes in embodied energy use have shared this focus on rebound from re-spending following increased efficiency in household rather than industrial energy use.

The crucial determinant of negative rebound findings in the Turner (2009) and Lecca *et al*. (2014) studies is how negative multiplier effects in energy sector supply chains (which in both cases are more energy-intensive than the supply chains of non-energy goods and service) enter the rebound calculation. In both of these studies, all changes in energy use that are driven by economic responses to increased energy efficiency are considered only within the ‘actual energy savings’ (AES) that constitute the numerator in the standard rebound calculation. The ‘potential energy savings’ (PES) in the numerator are entirely associated with the expected engineering savings from the technological change that gives us the energy efficiency improvement:

$$R = \left(1 - \frac{AES}{PES}\right) x100 \qquad [1]$$

However, this approach is disputed by Guerra and Sancho (2010). They argue that negative multiplier effects in the energy supply chain (that is, reductions in both direct and indirect use of energy by energy producers in producing output no longer required due to the engineering savings) should also be incorporated into the ‘potential energy savings’ that constitutes the denominator of the standard rebound calculation. Treating negative multiplier effects in energy supply as elements of both potential energy savings means that their (negative) impact on actual energy savings is effectively cancelled out. If not, Guerra and Sancho argue that there will be downward bias on rebound in what they refer to as a general equilibrium economy-wide context.

In considering this issue, Turner (2013) contends that since particularly indirect energy savings in energy supply chains will not be known *ex ante* (unless policy analysts have access to appropriate IO models), practical considerations and the understanding of policymakers should overrule the strict general equilibrium conditions that Guerra and Sancho (2010) introduce. We would highlight that the general equilibrium context of the Guerra/Sancho argument itself could also be questioned. As noted in the introduction to this paper, Lecca *et al*. (2014) argue that IO models cannot be considered as fully general equilibrium because of the assumption of fixed nominal incomes and prices. On the other hand, Guerra and Sancho (2010) argue that it is the price fixity of IO model that makes it the appropriate framework in which to assess potential energy savings in a general equilibrium context because these "occur only when considering quantity adjustments, with no price effects at work" (p.6685). That is, they are not arguing that all economy-wide impacts on energy supply should be treated as potential energy savings, with price driven impacts constituting actual energy savings.

However, the Turner (2013) argument is not one of the general equilibrium definition of rebound. The implicit point is that indirect and economy-wide rebound effects are not really general equilibrium concepts. Rather, they are measures of what happens to energy use when we extend focus beyond the more efficient user and the energy use directly affected by the efficiency improvement. When we extend focus in this way economy-wide and general equilibrium models are appropriate for quantifying, rather than defining rebound as an indicator of the performance of energy efficiency initiatives. In terms of the focus on practical applications, Turner's argument involves defining potential energy savings in terms of how these are perceived and anticipated by policy analysists and decision makers.

However, the partial vs. general equilibrium focus of the debate highlights a more fundamental issue in terms of the practical policy context in which rebound may be used as an indicator of the effectiveness of energy efficiency instruments to deliver energy savings. Turner (2013) goes on to argue that focus on definition, measurement and reporting of a single 'rebound' measure beyond the direct level may mask the fact that there are both upward and downward pressures on energy use at an economy-wide level following an efficiency improvement. The basic issue is that, as the complexity of the response increases as we move the more efficient user's response to the change in the price of the relevant energy service delivered, so will the determinants of rebound. Thus, the question would seem to be one of transparency and clarity in how we introduce more levels and types of effects to rebound calculations. Moreover, it is also perhaps one of ultimately determining the limit to the usefulness of a single rebound measure as we expand our focus in the types of energy use, and energy users impacted by an efficiency improvement at the micro level.

The objective of the current paper is to attempt to introduce some transparency to the treatment of indirect rebound through re-spending effects using embodied energy and multipliers (we also consider energy-related CO_2 emissions as a key driver of climate change). The motivation for this is that many policy analysts are familiar with use of the demand-driven input-output model, or at least with application of multipliers derived from it, for scenario analysis. On this basis, the focus of the applied study that follows is, for each of a small set of simple scenarios, to first identify and apply multipliers that allow us to generate an information set on the potential changes in energy use (and related CO_2 emissions) due to re-spending effects. We then demonstrate how these enter both the Guerra/Sancho and Turner rebound calculations (along with a third 'intermediate' option between these two extremes), and assess how the results may or may not add clarity and value in a policy context.

3. Input-output multiplier method – single region and interregional extension for energy use embodied in supply chains

3.1. Decomposition of multipliers in a single region environmental input-output model

For readers unfamiliar with IO approaches, the central equation that gives us the demand-driven environmental IO model used in studies of indirect rebound via re-spending is:

$$\varepsilon = e(I - A)^{-1}y \quad [2]$$

Where we have i, j=1,….N industries/outputs, this allows us to consider the impact of an Nx1 vector of final demands, *y*, on the Nx1 vector of physical energy use in each sector in the economy. Suppose we have information on the physical direct energy (or emissions) intensity of each sector *i*, e_i, given by dividing actual direct physical energy use (or emissions generated), ε_i, by sectoral output, x_i (in monetary units/value terms) in the accounting year in question. Then equation [2] allow us to consider how the Nx1 vector of (direct) energy use in each industry, ε, is driven by the Nx1 vector of final demands, *y*, (also in value terms) applying in that year. The transmission mechanism that gives us the demand-driven IO model is the NxN Leontief inverse or output multiplier matrix $(I - A)^{-1}$, which we will refer to as *L*. The elements of the NxN matrix *A* are the input-output coefficients a_{ij} which tell us the intermediate input purchases of output from sector *i* that are required (and reported in the IO table for the accounting year in question) per unit of total input in sector *j*. Subtracting *A* from the NxN identity matrix, *I*, and inverting we have the multiplier matrix, *L* with elements b_{ij} which then tell us the total amount of output (in value terms) in sector *i* that is required to support production of one unit of output demanded by final consumers in sector *j*. In extended form, for i, j=1,…N industries/outputs, *L* is given by:

$$L = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix} \quad [3]$$

The column totals of [3] give us the familiar output multipliers telling us the total output required across all sectors per monetary unit of final demand for the output of sector *j*. In each column where i=j, the element will b_{ij} includes the single unit (£1m, $1m etc.) of final demand driving the multiplier (the direct effect).

In the environmental IO model, [2] is extended through computation of a 1xN row vector of output-energy use (or emissions) multipliers, *eL*. However, we can consider the composition of these multipliers in the same manner as [3] allows us to consider the composition of the output multiplier for each sector/column j. If we arrange the Nx1 vector of output-energy use coefficients *e* from [2] along the main diagonal of a diagonal matrix, the result is the $N \times N$ matrix E:

$$E = \begin{bmatrix} e_1 & 0 & \dots & 0 \\ 0 & e_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e_N \end{bmatrix} \quad [4]$$

To generate the matrix of output-energy use multipliers and the environmental IO, E matrix is pre-multiplied to the Leontief inverse, *L*, so that we have an NxN matrix *EL*:

$$EL = \begin{bmatrix} e_1 b_{11} & e_1 b_{12} & \dots & e_1 b_{1n} \\ e_2 b_{21} & e_2 b_{22} & \dots & e_2 b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ e_n b_{n1} & e_n b_{n2} & \cdots & e_n b_{nn} \end{bmatrix} \qquad [5]$$

Thus, the column totals of [5] give us the output-energy (or emissions, depending on what we report in *e*) multipliers telling us the total amount of energy use required across all sectors per monetary unit of final demand for the output of sector *j*. In each column where i=j, the element will $e_i b_{ij}$ includes the single unit (in physical units) of direct energy use in sector *j* involved in producing the single monetary unit of final demand that drives the multiplier.

In applying the multipliers in the context of a marginal change in final demand a vector of changes in final demand, Δy is introduced to equation [2] in place of the base year *y*.[4] However, use of the extended multiplier matrices in [3] and [4] allows us to decompose the sectoral level impacts on output (in value terms) and embodied energy use (in physical terms) respectively.

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[4] Note that using the demand-driven IO model to consider marginal *changes* in final demand involves restrictive assumptions regarding fixed prices, universal Leontief (fixed proportions) technology and perfectly elastic supply (see Miller and Blair, 2009). This is the main reason why modellers often prefer to move to a more flexible CGE modelling framework – that incorporates an IO database but relaxes these assumptions - for scenario analyses. Nonetheless, IO remains commonly used particularly in policy communities, particularly given its transparency as a basic economy-wide modelling framework.

This involves introducing the change in demand for each sector's output, Δy_j, in the form of a diagonal matrix:

$$\Delta Y = \begin{bmatrix} \Delta y_1 & 0 & \dots & 0 \\ 0 & \Delta y_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \Delta y_N \end{bmatrix} \qquad [6]$$

If we post-multiply [6] to [5] we have:

$$EL\Delta Y = \begin{bmatrix} e_1 b_{11} \Delta y_1 & e_1 b_{12} \Delta y_2 & \dots & e_1 b_{1n} \Delta y_n \\ e_2 b_{21} \Delta y_1 & e_2 b_{22} \Delta y_2 & \dots & e_2 b_{2n} \Delta y_n \\ \vdots & \vdots & \ddots & \vdots \\ e_n b_{n1} \Delta y_1 & e_n b_{n2} \Delta y_2 & \cdots & e_n b_{nn} \Delta y_n \end{bmatrix} \qquad [7]$$

Reading along the rows of a matrix computed using [7] allows us to consider the change in total direct energy use in each sector *i* (row total) decomposed in terms of output produced to meet final demand for each sector *j*. Reading down the columns we can consider the sectoral composition in the change in total direct plus indirect energy use throughout the economy triggered by the change in final demand for output of sector *j*.

In policy analysis it will often be the case that multiplier values (generally column totals of [3] or [5]) would be extracted and directly applied to estimates of change in a given type of final demand. Similarly, if we want to focus on impacts in particular sectors of the economy, it is possible to extract any particular element(s), $e_i b_{ij}$ of interest from [5] and consider the impact of a change in final demand, Δy_j, for the sector in question.

3.2. Extension to interregional multiplier analysis of global supply chain impacts

Given the increasingly international nature of supply chain activity, and policy interest in consumption-based 'footprint' measures, it is also useful to extend the system above in an inter-regional context. This facilitates consideration of embodied energy (and/or emissions) impacts at an industrial level in other regions/countries. This may be of particular importance in circumstances where energy supply chain activity – which more efficiency consumers substitute spending away from – may be largely domestic (e.g. UK electricity supply), while supply chain activity for other goods and services – which spending is reallocated to – may be more international. If we extend to a case where we have r,s=1,….,T producing and consuming regions/countries, each with i,j=1,….,N industries/outputs the interregional variant of the demand driven IO model extends EL and $EL\Delta Y$:

$$EL(global) = \begin{bmatrix} e_i^1 b_{ij}^{11} & \cdots & e_i^1 b_{ij}^{1s} & \cdots & e_i^1 b_{iN}^{1T} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_i^1 b_{ij}^{r1} & \cdots & e_i^r b_{ij}^{rs} & \cdots & e_i^r b_{iN}^{rT} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_N^T b_{Nj}^{T1} & \cdots & e_N^T b_{Nj}^{Ts} & \cdots & e_N^T b_{NN}^{TT} \end{bmatrix} \quad [8]$$

$$EL\Delta Y(global) = \begin{bmatrix} e_i^1 b_{ij}^{11} \Delta y_j^1 & \cdots & e_i^1 b_{ij}^{1s} \Delta y_j^s & \cdots & e_i^1 b_{iN}^{1T} \Delta y_N^T \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_i^1 b_{ij}^{r1} \Delta y_j^1 & \cdots & e_i^r b_{ij}^{rs} \Delta y_j^s & \cdots & e_i^r b_{iN}^{rT} \Delta y_N^T \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_N^T b_{Nj}^{T1} \Delta y_j^1 & \cdots & e_N^T b_{Nj}^{Ts} \Delta y_j^s & \cdots & e_N^T b_{NN}^{TT} \Delta y_N^T \end{bmatrix} \quad [9]$$

Use of [9] and the underlying output-energy multiplier matrix in [8] - or results for elements thereof – allows us to consider impacts of a change in a particular type of final consumption demand (e.g. UK household expenditure), for the outputs of any sector *j* in any region *s* (where s≠UK, this means a direct import from another country) on energy use in any sector *i* in any producing region *r*. The main diagonal of sub-matrices in each [8] and [9] gives us own-country impacts where r=s. The off-diagonal sub-matrices give us impacts of spending by final consumers located in country *s* on own-country goods and services or imports that have impacts on embodied energy use in other countries.

The system in [9] also provides information to calculate re-spending rebound effects – using the contested methods proposed by Guerra and Sancho (2010) and Turner (2013) – at different spatial scales by informing the AES and/or PES elements of the standard rebound calculation in [1]. The multi-country spatial focus introduced below is a novel development in the rebound literature more generally, where indirect and economy-wide rebound studies tend to focus on impacts on energy use within a given regional or national economy.[5]

4. A simple illustrative application for potential re-spending decisions

4.1. Data and simulation strategy

The applied examples in this section involve use of the environmental interregional IO accounts reported as part of the World Input-Output Database (WIOD) project (Timmer *et al*., 2015) to calculate the components underlying equation [8].[6] The WIOD database is reported for N=35 industries in T=41 regions/countries (40 countries plus a composite 'Rest of the World', ROW, region). The countries identified are listed in Appendix A while the definition of the 35 industries

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[5] Economy-wide rebound is considered in a global interregional context in a CGE analysis of increased energy efficiency in German industries by Koesler et al. (2015).

[6] The WIOD database can be accessed at http://www.wiod.org/new_site/home.htm. Here we use the 2009 IRIO table that can be downloaded at http://www.wiod.org/new_site/database/wiots.htm and corresponding 'Energy use emissions relevant' and 'CO2 emissions' data (limited to CO2 emissions from energy use) for each country at http://www.wiod.org/new_site/database/eas.htm that allow to construct the E matrices for energy use and CO2 emissions respectively.

is detailed in Appendix B. We use data for the most recent year that WIOD data are reported for both the economic and environmental components of the system, which is 2009.

It is important to note that the complex process of constructing global interregional input-output data – where there is a need to harmonise bi- and multi-lateral trade data, convert all economic data to basic (producer) prices reported in a consistent currency (millions of US dollars) etc. – sacrifices have to be made particularly in terms of industry level detail/sectoral disaggregation.[7] A key problem area in considering embodied energy use (and energy-related GHG emissions) using the WIOD database is the aggregation of electricity, gas and water supply in a single industry. Moreover, the time taken to construct complex inter-country IO databases inevitably leads to a delay in reporting for recent accounting years. Here, the need to rely on data for 2009 may be considered problematic given the timeframe of disruption due to the financial crisis. However, in the context of the current paper, we consider these data adequate for the purpose of numerical illustration of the methods discussed above.

To help make our calculations as transparent as possible we take the simple example of a 10% efficiency improvement in the use of electricity and gas by all UK households. However, given the identification of only an aggregate ‘Electricity, Gas and Water Supply’ industry (hereafter referred to as EGWS) in the data (see Appendix B) we extend this to increased efficiency in water use. This involves no direct energy use by households but will involve energy use embodied in water supply.

We begin, in Section 4.2, by using embodied energy and CO_2 multiplier values extracted from computation equation [8] to examine the composition of the multiplier for j=EGWS, focussing on the r=UK sector (where, according to the WIOD data used, over 99% of UK household spend is concentrated). We then consider the composition of the absolute reduction in energy use embodied in the EGWS supply chain when we introduce a 10% reduction in UK household spending to give us the change in final demand, *y*, using [9].

Then, in Sections 4.3-4.5, we consider three alternative scenarios of how spending may be reallocated (i.e. to give a corresponding positive change in *y* in calculation of [9]). The specification of scenarios for re-spending is again made simple, focussing on reallocation to a single type of good or service in each case, to aid transparency of what is intended to be a simple illustrative scenario. We draw on information provided by Chitnis *et al*. (2013) to identify

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[7] This is generally the case in terms of the limited range of global interregional databases available for IRIO analyses. For example, the evolving OECD intercountry IO database project is reported for 34 industries (see http://www.oecd.org/trade/input-outputtables.htm). The dataset provided by the Global Trade Analysis Project, GTAP (https://www.gtap.agecon.purdue.edu/databases/v7/) reports 57 sectors, but with focus sectoral level detail being largely centred on in agricultural production. GTAP does separately identify gas, electricity and water supply (a key aggregation problem with the WIOD and OECD databases), but with the most recent accounting year being 2004.

goods/services with relatively high income elasticities for UK households.[8] However, our choice of good/services to redirect spending towards is also motivated by moving from a good/service where UK spending is largely domestic (spending in 'Hotels and Restaurants') to ones involving more spending on imports and greater reliance on external supply chains ('Food, Beverage and Tobacco' and 'Air Transport'). This allows us to gradually introduce more focus on spatial impacts on energy use and CO_2 embodied in global supply chains and indirect rebound beyond the boundaries of consumers' home economy.

Moreover, in considering how the resulting increases and decreases in direct and indirect energy use translate to calculation of rebound (equation [1]) under the arguments of Guerra and Sancho (2010), Turner (2013) and a third, 'intermediate' treatment, we abstract from consideration of any direct rebound in household use of electricity and gas. This allows us to focus in a transparent way on whether any net negative impact on energy use translates to positive or negative indirect rebound at different spatial levels.

4.2. Target of energy efficiency improvement: 'Electricity, Gas and Water Supply'

In the WIOD database for 2009 UK households are recorded as spending $55,258m (producer prices) on combined 'electricity, gas and water supply' (EGWS) outputs. 99.4% of this is directed at the UK sector. According to the WIOD environmental satellite data, the total spend incorporates use of 1,525,911terajoules (tj) of electricity and natural gas (1,084,516tj and 441,395tj respectively). This is the direct energy use that would be the subject of any efficiency improvement in how households use energy. So, in the context of our 10% increase in the efficiency with which households use electricity and gas (and water), this implies that households can heat and light their homes to the same extent but requiring 10% less physical energy. That is, a potential direct engineering energy saving of 152,591tj for a 10% reduction in household final demand spending on EGWS output. For simplicity, we abstract from any investment activity that may be involved in introducing the efficiency improvement and assume that the full potential energy saving is realised. In terms of related CO_2 emissions, according to the WIOD data for our accounting year of 2009, UK households directly generated 61,716 kilo-tonnes (kt) of CO_2 in their use of gas. There is no direct generation of CO_2 in using electricity so the gas figure alone gives us a direct CO_2 saving of 6,171.6 kilo-tonnes corresponding to the 44,139.5tj gas component of the total 152,591 tj direct energy saving.

In the next sub-section we turn our attention to the question of how might UK households reallocate this spending. However, first we must consider the embodied energy use implications of the change in demand for EGWS outputs and how this translates to the

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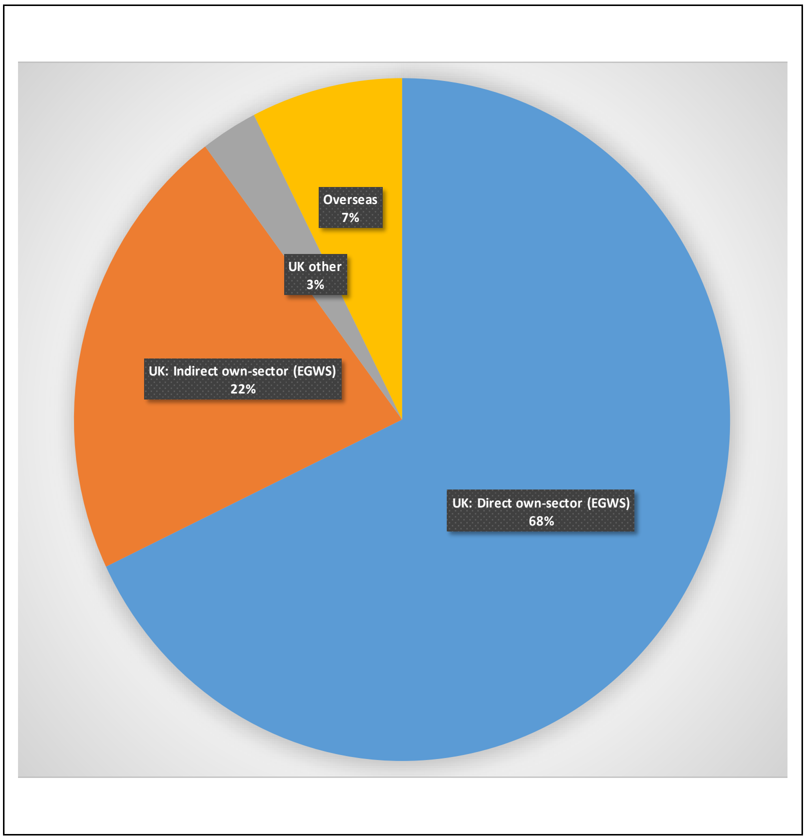
[8] We use income elasticity data on the basis that we are looking at a reallocation of spending that results from real income savings as the cost of energy services facilitated by gas and electricity use falls with an efficiency improvement.

alternative treatments of negative embodied energy multiplier effects in the ‘general equilibrium’ rebound debate outlined above.

When we calculate the interregional output- energy multiplier matrix using [8], the column total for j=EGWS and s=UK is 38.14. This tells us that for every $1m final demand expenditure by any type of final consumer (including but not limited to UK households) 38.14tj of energy is required throughout the global supply chain of this sector. Within the element of this column where i=j=EGWS and r=s=UK we have the direct energy use within EGWS itself, 25.9tj, which equates to 68% of the total multiplier value (see Figure 1).

Figure 1: Distribution of the 38.14tj per $1m (USD) output-energy multiplier for the UK Electricity, Gas & Water Supply Sector (WIOD 2009)



Another 8.33tj (22% of the total) is incorporated in this entry is (indirect) energy use within the EGWS sector required to produce $1m of output to meet final demand (i.e. the own-sector multiplier effect). Given the level of aggregation over electricity, gas and water supply in the WIOD EGWS sector, much of this is likely to in fact be inter-sectoral interactions (e.g. sales from the gas

A further 1.06tj (just under 3% of the total in Figure 1) is embodied in the UK supply chain, the bulk of which (84%) is in the j=Mining and Quarrying sector (including the off-shore oil and gas extraction industry). Summing down the r=UK entries in the j=EGWS, s=UK column gives us the UK component of the global output-energy multiplier, which gives us just under 93%, or 35.3tj, of the 38.14 total.

The other 7%, 2.84tj of energy use per $1m output to meet final demand for EGWS is located overseas and given by summing down the r≠s entries of the column. Again, this can be decomposed in terms of which industries in which country the direct energy use is located. The largest shares of the 2.84tj external effect are located in the composite ROW region (54% of the overseas requirement, 4% of the total multiplier) and Russia (19% and 1.4%).[9] Within r=ROW, the two largest shares of the UK EGWS multiplier are in i=EGWS (most likely gas supply) and i=Mining and Quarrying, but with impacts in other, mainly petroleum refining, metal manufacture and transport, activities. A similar pattern is observed in the Russian case.

However, Figure 1 summarises the basic result that the bulk of energy use embodied in the UK EGWS global supply chain is in fact located within the UK, and most of that in terms of own-sector energy use (both direct and indirect). When we calculate the multiplier matrix in [8] using CO_2 intensities in place of energy intensities in *E* a similar pattern emerges for j=EGWS in s=UK. (Note again that the CO_2 data reported in the WIOD dataset is limited to energy-related emissions.) The total output-CO_2 multiplier 1.89kt, 67% of which is direct energy use in EGWS, 21% is the indirect own-sector effect, a further 4% being the remainder of the 1.74kt own-country multiplier, while the remaining 8% of the 1.89kt total located in production overseas.

Now let us consider how the output-energy (and output-CO_2) multipliers calculated using [8] determine the embodied energy (and CO_2) impacts of the $5,526m reduction in UK household final consumption spending on EGWS that we associate with a 10% increase in efficiency in the use of electricity, gas and water. For simplicity, given that 99.4% of UK household spend on EGWS is in the UK sector, we will assume that the entire demand shock is directed there. This means that there will only be one entry – Δy_j^s where j=EGWS and s=UK – in the interregional variant of the diagonal *Y* matrix that is post-multiplied to the output-energy multiplier matrix to give us the results of the shock via equation [9]. The main reason for making this assumption at this stage is to provide the basis for a simple exposition of how the EGWS multiplier values discussed above can be used to compute the impacts of a change in demand (in the examples in Sections 4.4. and 4.5. we introduce shocks impacting both UK and non-UK sectors).

In Table 1 we report the results of applying the UK EGWS output-energy and output-CO_2 multipliers to the $5,526m reduction in demand for that sector's output. However, at the top of the table we first report the associated direct reduction in household energy use and CO_2 emissions. This item – labelled A – adds to the embodied supply chain effects in giving us the total change in energy use. It is also the direct engineering effect (assuming no direct rebound, as explained above) that forms the undisputed part of the 'potential energy savings' (PES) in the rebound calculation [1], which we report in Table 2. However, before we consider rebound, let us focus on the actual changes in energy use estimated using the demand-driven IO model.

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[9] One of the benefits of the evolving OECD inter-country global IO database - http://www.oecd.org/trade/input-outputtables.htm - is greater disaggregation of what is the composite ROW region in WIOD, in particular to identify key oil and gas extraction/supply countries such as Saudi Arabia.

Table 1: Changes in energy use and CO2 emissions associated with a 10% reduction ($5,525.8m) in UK household use of UK EGWS outputs

	Energy use (terajoules)	**Related CO_2 (kilotonnes)**
A. Reduction in direct energy use by UK households	-152,591	-6,172
Reductions in energy use in UK EGWS supply chains:		
Total multiplier effect per $1m spend:	*38.14*	*1.89*
B. Direct - own-sector *(25.9tj/1.26kt per $1m)*	-143,142	-7,777
C. Indirect - own-sector *(8.33tj/0.41kt per $1m)*	-46,040	-2,501
D. Indirect - other UK *(1.06tj/0.08kt per $1m)*	-5,878	-471
Sub total UK	**-195,060**	**-10,749**
E. Indirect - outside of UK *(2.84tj/0.15kt per $1m)*	-15,713	-926
Global total	**-210,773**	**-11,675**
Total reduction in UK energy use	**-347,651**	**-16,921**
Total reduction in global energy use	**-363,364**	**-17,847**

In the second row of results in Table 1 we report the total global multiplier values, which may be multiplied by the direct shock of value of $5,525.8m to give (with some impact of decimal places underlying the figures reported in the title and body of the table), the total change (reduction) in global energy use in the row labelled ‘Global total’. However, we have also reported the key components of the overall multiplier values as items B-E so that we can distinguish own-sector effects from energy use/emissions embodied in the wider UK and global supply chains. Note that it would be possible to further break these results out by country and industry in more detailed analysis.

Table 2: Reduction in EGWS spend: embodied energy and CO_2 rebound calculation

	Energy use	CO_2
Actual energy savings (AES):		
UK level	347,651	16,921
Global level	363,364	17,847
Potential energy savings and rebound:		
1. Guerra and Sancho (2010) - all included in PES		
UK level:		
PES (A, B, C, D)	347,651	16,921
Rebound	**0%**	**0%**
Global level		
PES (A, B, C, D, E)	363,364	17,847
Rebound	**0%**	**0%**
2.Intermediate: EGWS direct included in PES:		
UK level:		
PES (A and B)	295,733	13,948
Rebound	**-18%**	**-21%**
Global level:		
PES (A and B)	295,733	13,948
Rebound	**-23%**	**-28%**
3. Turner (2013) - only household direct saving included in PES		
UK level:		
PES (A)	152,591	6,172
Rebound	**-128%**	**-174%**
Global level:		
PES (A)	152,591	6,172
Rebound	**-138%**	**-189%**

However, for our purposes here, the key point is that the initial reduction in household energy use and related CO_2 emissions (again, abstracting from any direct rebound effect) from the 10% efficiency improvement in electricity, gas and water use is accompanied by reductions in energy use throughout the EGWS supply chain. Moreover, given the energy – and CO_2 – intensity of this supply chain, these additional reductions are substantial relative to the direct change in household energy use and CO_2 generation.

Our key point of interest in this paper is how the absolute changes in energy use from household re-spending decisions following an energy efficiency improvement (but, given the IO modelling context, before any changes in nominal incomes and prices occur) may enter the calculation of the indirect rebound effect. Where the change in energy use is negative (a reduction), this implies positive energy savings in equation [1] and Table 2 so that rebound is less than 100%. While the changes in energy use considered thus far do not involve any reallocation of the reduction in spending on EGWS, it is useful to consider how the results in Table 1 enter the different definitions of indirect rebound discussed in Section 2. This provides us an ‘anchor’ to set subsequent results against. In Table 2 we consider three different definitions of rebound.

The first is that proposed by Guerra and Sancho (2010) where all of items in Table 1 are considered as both potential (anticipated) and actual energy savings (PES and AES in equation [1]). This means that, with no reallocation of spending, in reference to equation [1] AES=PES and we have rebound of zero at both UK and global levels. The second (presented as item 3 in Table 2) is that applied in the Lecca *et al.* (2014) study, and which Turner (2013) argues in favour of, where only the ‘direct engineering effect’ of the change in household energy use directly associated with the efficiency improvement enters PES. This means that all changes in energy use in the EGWS supply chain (both direct within that sector in producing the $5,526m worth of output no longer demanded, and indirect in the supply chain) effectively constitute (negative) rebound against the direct (engineering) effect in household energy use. In other words, AES is greater than PES and rebound is negative.

We have also added a third potential definition of rebound in Table 2 (presented as item 2). Turner’s (2013) main argument against the Guerra and Sancho (2010) definition is that PES should be defined in terms of energy savings that are *anticipated* by policymakers. It may be argued that, even in the absence of an IO model such as the one we have here, policymakers may anticipate changes in direct energy use in the impacted energy supply sector and account for this in what they hope to realise as a result of implementing any energy efficiency initiative. This is presented as the second set of rebound results in Table 2 as it constitutes something of an intermediate case between the definitions argued by Guerra and Sancho (2010) and Turner (2013) because the PES includes item B but not C-D (UK level rebound) or C-E (global level rebound) from Table 1. As in the Turner (2013) case, the reductions in embodied energy use from negative multiplier effects elsewhere in the EGWS chain (items C-E) effectively give us a gross (but smaller) negative rebound effect.

In the demand-driven IO model, there are no price changes to potentially provide an off-setting boost to demand from both the more efficient UK households and other intermediate and final consumers. Therefore, these negative components in the second and third rebound definitions in Table 2 will remain and offset positive rebound pressures from re-spending decisions (although there is likely to be positive multiplier impacts on EGWS in all cases). We now turn our attention to a set of simple examples of potential re-spending decisions. However, a basic prediction can be made that unless the supply chains of any goods/services that spending is redirected towards are more energy- and/or CO_2 intensive than that of the energy supply sector where demand is reduced (here UK EGWS), the negative impacts in Tables 1 will mean that a net reduction in global (industrial) energy use and/or CO_2 generation will occur (along with the reduction in household energy use and emissions). Whether this translates to a net negative indirect rebound effect will depend on which of the three definitions identified in Table 2 is considered appropriate.

4.3 Target of spending reallocation: ‘Hotels and Restaurants’

In practice a scenario where UK households make decisions on reallocating the $5,526m of spending saved as efficiency improves in their use of electricity, gas and water supply is likely to involve spending on outputs of multiple domestic and external sectors. However, to keep things simple and transparent in line with the objectives of this paper we consider a limited set of ‘one for one’ substitutions. This allows us to focus on potential impacts of different types of spend (such an approach could in fact be useful in practice in informing policymakers aiming to influence re-spending decisions). Our first example is one where the $5,526m is reallocated from spend on UK EGWS in favour of outputs of the UK ‘Hotels and Restaurants’ sector. This target for reallocation is motivated (but not quantified) first by the relatively high income elasticity (0.68) estimated for this type of spending for UK households in Chitnis *et al*. (2013). The decision to focus on the UK sector, and thus a single multiplier value for each energy and CO_2, is motivated by the fact that, again according to the WIOD 2009 data, 95% of UK household spending on ‘Hotels and Restaurants’ is in the domestic sector.

As in Section 4.3 for EGWS, we extract information on the output-energy (and output-CO_2) multiplier from matrix calculated using [8], here focussing on the column total for j=Hotels and Restaurants and s=UK, which takes the value of 2.8. This tells us that for every $1m of final demand expenditure by any type of final consumer (including but not limited to UK households), 2.8tj of energy is required throughout the global supply chain of the ‘Hotels and Restaurants’ sector.

The first thing to note is that the output-energy multiplier for this type of spend is considerably lower than the 38.14tj per $1m final demand that spending has been reallocated away from. Similarly, the corresponding output-CO_2 multiplier for UK 'Hotels and Restaurants', at 0.14kt per $1m is low relative to the corresponding EGWS figure of 1.8kt. Therefore, we clearly expect a net negative impact on global energy use and CO_2 emissions. However, before we turn our attention to this, let us consider how the composition of the 'Hotels and Restaurants' multipliers differs.

Figure 2: Distribution of the 2.8tj per $1m (USD) output-energy multiplier for the UK Hotels and Restaurants Sector (WIOD 2009)

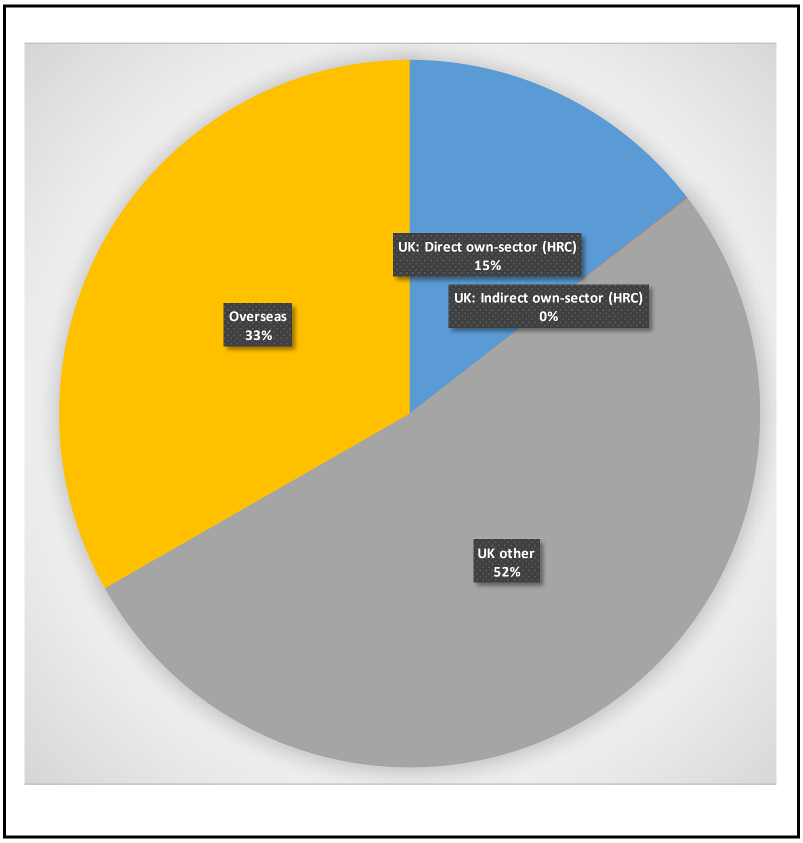

Figure 2 shows that own-sector energy use (both directly associated with the $1m final demand and indirectly through the intra-sectoral element of the supply chain) in UK 'Hotels and Restaurants' is much less important in contributing to the total global multiplier than found above for the case of UK EGWS. 52%, or 1.48tj of the 2.8tj total is indirect energy use in the UK supply chain (with the same share applying for the output-CO_2 multiplier). Detailed analysis of the j= Hotels and Restaurants, s=UK column of the matrix calculated from [8] reveals that the largest contributor to this is 0.56tj per $1m generated in the UK EGWS sector (equating to just under 30% of the total global multiplier). The other two main contributors in the UK supply chain are energy use in the 'Agriculture, Hunting, Forestry and Fishing' sector (0.3tj per $1m) and 'Food, Beverage and Tobacco' (0.24tj).

Table 3: Changes in energy use and CO_2 emissions associated with reallocation of $5,525.8m spending between UK EGWS and Hotels & Restaurants outputs

	Energy use (terajoules)	Related CO_2 (kilotonnes)
Increases in energy use in UK Hotels and Restaurants supply chain:		
Total multiplier effect per $1m spend:	*2.84*	*0.14*
F. Direct - own-sector *(0.41tj/0.02kt per $1m)*	2,287	101
G. Indirect - own-sector *(0.001tj/0.000kt per $1m)*	6	0
H. Indirect - other UK *(1.48 tj/0.94kt per $1m)*	8,199	413
Sub total UK	**10,492**	**514**
I. Indirect - outside of UK *(0.94tj/0.05kt per $1m)*	5,218	279
Global total	**15,711**	**794**
Net increase/decrease in UK and global energy use:		
Change in direct energy use by UK households (A)	-152,591	-6,172
EGWS shock: change in direct EGWS energy use (B)	-143,142	-7,777
Change in other UK energy use (C, D, F, G, H)	-41,426	-2,458
Net at UK level	**-337,159**	**-16,406**
Change in energy use outside of UK (E and I)	-10,495	-646
Net at global level	**-347,654**	**-17,053**

In terms of the 33% of the global multiplier value involving energy use in overseas production (for CO_2 the corresponding share is slightly larger at 35% with a lower share of the multiplier accounted for by direct own-sector emissions), this is spread across multiple countries. However, the largest group share of the overseas impact (just under 30%, or just under 10% of the total output-energy multiplier value) is located in other EU nations.[10] The industry composition of overseas impacts is also dispersed across multiple industries, with external agricultural, food and drink sectors prominent alongside external EGWS (again, likely to be mainly gas supply serving the UK EGWS sector), transport activities and a number of manufacturing activities.

However, while indirect impacts on energy use embodied in the UK and global supply chains are important relative to the overall UK 'Hotels and Restaurants' output-energy and CO_2 multipliers, Table 3 shows that the results of applying this multiplier to the $5,526m that is available for reallocation have little impact on the reduction in global energy use and CO_2 generation from reduced spend on UK EGWS. Again, in the top half of Table 3 we have broken

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[10] Note that the WIOD database was constructed before Croatia joined the EU and this country is not separated from the composite ROW region.

down the multiplier calculations to consider different elements of the impact within and outside of the UK and labelled these F-I, to follow on from A-E identified for the reduction in UK EGWS spend in Tables 1 and 2. In the bottom half of Table 3 we then bring the corresponding elements together to report net impacts on energy use and CO_2 generation within and outside the UK.

In Table 4 we then introduce elements F-I to the AES component of the indirect rebound calculation at UK and global levels, and report results for the three definitions of rebound (where it is the PES component determined in Table 2 that is variable across the three). Where this results in positive AES (reduced energy use) that is less than PES, this will give us rebound greater than zero but less than 100%. The results show that increased energy use in the UK 'Hotels and Restaurants' supply chain is sufficient to bring about a small positive indirect rebound (again emphasising that we abstract from any consideration of direct rebound effects in UK household use of gas and electricity) under the Guerra and Sancho (2010) definition. However, it does little to offset the net negative indirect rebound under the other two definitions (i.e. AES is still greater than PES).

Table 4: Reallocation of UK EGWS spend to UK Hotels and Restaurants: embodied energy and CO2 rebound calculation

		Energy use	CO_2
Actual energy savings (AES):			
	UK level	337,159	16,406
	Global level	347,654	17,053
Rebound:			
1. Guerra and Sancho (2010) - all included in PES			
	UK level:	3%	3%
	Global level:	4%	4%
2.Intermediate: EGWS direct included in PES:			
	UK level:	-14%	-18%
	Global level:	-18%	-22%
3. Turner (2013) - only household direct saving included in PES			
	UK level:	-121%	-166%
	Global level:	-128%	-176%

4.4 Target of spending reallocation: 'Food, Beverages and Tobacco'

The second target for reallocation of the \$5,526m saved from reduced spend on EGWS is 'Food, Beverages and Tobacco' (hereafter FBT). The income elasticities for spend in this area reported by Chitnis *et al*. (2013) are lower (0.18 for food and non-alcohol and 0.29 for alcohol and tobacco) than for spend on 'Hotels and Restaurants'. However, FBT makes an interesting study in terms of the pattern of UK spend and imports, and of UK vs. global energy use (and CO_2) impacts. The output-energy and output-CO_2 global multiplier values are 5.97tj and 0.29kt respectively per \$1m final consumption demand, which are larger than those for UK 'Hotels and Restaurants' (2.8tj and 0.14kt) but smaller than those for UK EGWS (38.14tj and 1.8kt). In both cases the EGWS and agricultural industries dominate in terms of indirect impacts in the UK supply chain.

However, the overseas components of the UK FBT multipliers are smaller (24% for embodied energy and 27% for CO_2) than that of 'Hotels and Restaurants' (33% in Figure 2). On the other hand, the share of spend on the UK sector is much smaller. Only 44.3% of UK household spend on the outputs of the global FBT industry is in the UK sector. The remainder is imported from a wide range of countries identified in the WIOD database, which have output-energy and output-CO_2 multiplier values ranging from 4.35tj and 0.23kt per \$1m (Ireland, where 6% of UK household spend is made in the 2009 WIOD database) to 13.84tj and 1.32kt (India, just 0.2% of UK household spend). The 'country' with the highest multiplier values (8.77tj and 0.46kt) and highest share of UK spend (9.6% of total spend, 17% of imports) is the composite ROW region, followed by the Netherlands (5.42tj, 0.28kt and 7.7% of spend) and Germany (6.0tj, 0.3kt, 6.4%).[11]

Taking a weighted (based on share of UK household spend) average of the global output-energy and output-CO_2 multiplier values across all countries gives us figures of 6.32tj and 0.31kt respectively, which are slightly higher than those for the UK sector (5.97tj and 0.29kt from above). If we introduce the \$5,526m reallocation in line with the distribution of initial (2009) UK household spending on FBT, these weighted multiplier values give us impacts on global energy use and CO_2 of 34,898tj and 1,737kt respectively. These figures correspond to the 'Global total' results reported in the top half of Table 5.

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[11] At this point it is important to remember that the WIOD FBT sector incorporates production a wide range of goods and services, and its composition in this respect will vary across different countries. This, combined with differences in production technologies to determine differences in output-energy and output-CO_2 multiplier values. However, while the issue of over-aggregation is problematic in terms of accuracy of IO-based multiplier analysis (and one that impacts here particularly through reporting of the aggregate EGWS sector), it is recognised in the wider literature as a necessary cost of gaining insight on international trade impacts through use of an IRIO system such as OECD (Hawdon and Pearson, 1995; Lenzen *et al*. 2004).

Table 5: Changes in energy use and CO_2 emissions associated with reallocation of \$5,525.8m spending between UK EGWS and global Food, Beverage and Tobacco outputs

	Energy use (terajoules)	Related CO_2 (kilotonnes)
Increases in energy use in global Food, Beverage, Tobacco supply chain:		
J. In UK related to UK spend	11,025	508
K. In UK related to imports	275	15
Sub total UK	**11,300**	**522**
L. Outside UK related to UK spend	3,573	191
M. Outside UK related to imports	20,024	1,024
Sub total non-UK	**23,598**	**1,215**
Global total	**34,898**	**1,737**
Net increase/decrease in UK and global energy use:		
Change in direct energy use by UK households (A)	-152,591	-6,172
EGWS shock - change in direct EGWS energy use (B)	-143,142	-7,777
Change in other UK energy use (C, D, F, J, K)	-40,618	-2,450
Net at UK level	**-336,351**	**-16,398**
Change in energy use outside of UK (E, L and M)	7,885	289
Net at global level	**-328,467**	**-16,109**

However, using the IRIO system in equations [8] and [9] – where changes in *Y* are included for all j=FBT – we are able to decompose these impacts. While it would be possible to break down results at the level of impacts on each different industry, *i*, in each country, *r*, in Table 5 we focus at a more aggregate level where we consider impacts within and outside the UK depending on where increased spending is directed. The results in the top half of Table 5 show that, while only just under 56% of UK FBT spending is directed outside of the UK, 68% of the total energy impact and 70% of the CO_2 impact are felt overseas. Item L reports results for the overseas impact of UK spend (resulting from 24% and 27% of the UK FBT output-energy and CO_2 multipliers impacting outside the UK – and equating to the share of item L in the sum of J and L results). However, the largest share of the global impact is reported as item M, overseas impacts related to UK household imports of FBT.

That this result implies a net 'leakage' effect impacting overseas energy use and CO_2 emissions from re-spending following an improvement in energy efficiency by UK households is made clear in the second last row of Table 5. Here we observe a net increase in overseas energy use and CO_2 as a result of the reallocation of UK household spending between EGWS and FBT. That is, items L and M from the top half of Table 5 are sufficient to more than offset the decrease in energy use and CO_2 generation in the global energy supply chain reported as item E in Table 1.

The net positive leakage effect on energy use and CO_2 emissions is also reflected in all of the rebound calculations in Table 6 (there are gross leakage effects in all re-spending scenarios considered). Under the Guerra and Sancho (2010) approach the impact is not clearly distinguishable from what happens in Table 4 (for the 'Hotels and Restaurants' re-spend), where net negative impacts are observed at all levels but the gross positive impact on overseas energy use/CO_2 generation from the re-spend alone drives the difference between UK and global level rebound. This is because the entire indirect impact of the reduction in EGWS spend is part of PES.

However, under the other two approaches the energy and CO_2 leakage is reflected in the magnitude of the negative indirect rebound contracting for the first time as we move from UK to global level as overseas energy use and CO_2 increases. This means that we have a net positive rebound impact outside of the UK, which will be important where policymakers are concerned with the consumption-focused 'footprint' of policies aimed at addressing global problems such as climate change. However, the question that we are posing in this paper is whether one or other of the current (and conflicting) definitions of rebound provide the best means of communicating policy-relevant information such as this.

Table 6: Reallocation of UK EGWS spend to global Food, Beverage, Tobacco: embodied energy and CO_2 rebound calculation

		Energy use	CO_2
Actual energy savings (AES):			
	UK level	336,351	16,398
	Global level	328,467	16,109
Rebound:			
1. Guerra and Sancho (2010) - all included in PES			
	UK level:	3%	3%
	Global level:	10%	10%
2.Intermediate: EGWS direct included in PES:			
	UK level:	-14%	-18%
	Global level:	-11%	-15%
3. Turner (2013) – only household direct saving included in PES			
	UK level:	-120%	-166%
	Global level:	-115%	-161%

4.5 Target of spending reallocation: 'Air Transport'

The final scenario we consider is a reallocation of the $5,526m freed up from UK household spend on EGWS towards 'Air Transport. Chitnis *et al*. (2013) estimate the income elasticity for all 'non-private transport' activities to be relatively high at 0.5. This type of 'turning lights into flights' (as in the title of Chitnis *et al*., 2013) scenario, which is a relatively energy – and CO_2-intensive choice, may be regarded as unrealistic, just as our singular 'heat or eat' type scenario in the previous section. However, we reiterate that our intention is to present some simple illustrative and transparent scenarios that help us think through implications in terms of the information set provided by different definitions of the rebound effect.

Table 7: Changes in energy use and CO_2 emissions associated with reallocation of $5,525.8m spending between UK EGWS and global Air Transport outputs

	Energy use (terajoules)	Related CO_2 (kilotonnes)
Increases in energy use in global Air Transport supply chain:		
J. In UK related to UK spend	36,956	9,150
K. In UK related to imports	323	33
Sub total UK	**37,279**	**9,183**
L. Outside UK related to UK spend	4,578	262
M. Outside UK related to imports	60,728	3,910
Sub total non-UK	**65,306**	**4,172**
Global total	**102,585**	**13,355**
Net increase/decrease in UK and global energy use:		
Change in direct energy use by UK households (A)	-152,591	-6,172
EGWS shock - change in direct EGWS energy use (B)	-143,142	-7,777
Change in other UK energy use (C, D, F, J, K)	-14,639	6,210
Net at UK level	**-310,372**	**-7,738**
Change in energy use outside of UK (E, L and M)	49,593	3,246
Net at global level	**-260,779**	**-4,491**

'Air Transport' is interesting as the only case where global CO_2 multiplier values are larger than those of EGWS spend (based on the WIOD data). This is due to the types and CO_2 intensity of energy use in the underlying data. Each $1m spend on the UK sector has a global output-energy multiplier of 14.44tj and an output-CO_2 multiplier of 3.37kt (where, as in all sectors, the WIOD CO_2 data are directly related to reported energy uses). These multiplier values are almost entirely made up of direct effects in Air Transport (12.2tj and 3.10kt per $1m output respectively). However, only 52% of UK household spend is in the UK sector, with the next biggest share (10%) directed at the US sector. As in Section 4.4 for FBT we can construct average multiplier values for Air Transport output-energy and output-CO_2 multipliers using the distribution of UK household spend to weight components. These come out, respectively, as 18.6tj and 2.4kt per $1m final demand for output. While the former is lower, the latter is higher than the corresponding multipliers for UK EGWS (38.14tj and 1.8kt respectively). This tells us that the global multiplier effect of the £5,526m increase in spending on 'Air Transport' – again assuming that the pattern of a marginal increase in spending is the same as in the base year – will be smaller in terms of physical amount of energy use but larger for CO_2. This is confirmed by comparing the 'Global total' results in the top half of Table 7 with those with the same label in Table 1. It is the reduction in direct energy use and CO_2 generation by households (item A in all tables) that gives us a total net reduction in both energy use and CO_2 in the last row of Table 7.

Given the energy- and CO_2-intensity of Air Transport activity relative to that located overseas in the FBT case above, we observe smaller net reductions in global (but also UK) energy use and CO_2 generation and larger indirect rebound effects in Tables 7 and 8 relative to what we find in Tables 5 and 6. However, the more marked impacts on the alternative indirect rebound calculations in Table 8 give us the most 'food for thought' in considering the information set provided by each.

As in the FBT re-spend scenario in Section 4.4, with both direct and indirect EGWS sector impact counted within PES, the positive leakage effects of energy use and CO_2 generation overseas are simply reflected in an increase in the already positive indirect rebound effect as we move from UK to global level. On the other hand, under the intermediate treatment (where reduction in direct energy use within EGWS is included in PES but indirect EGWS supply chain effects are not), the net positive results in Table 7 more clearly map to changes in direction of the indirect rebound effect at both UK and global levels in Table 8. First, the positive net changes UK CO_2 generation outside of the direct household and EGWS impacts (A and B) cause indirect rebound in CO_2 at UK level to become positive. Second, increased energy use in overseas supply chains for both UK outputs and imports to UK household consumption causes indirect rebound in energy use to also become positive at the global level.

Table 8: Reallocation of UK EGWS spend to global Air Transport: embodied energy and CO_2 rebound calculation

		Energy use	CO_2
Actual energy savings (AES):			
	UK level	310,372	7,738
	Global level	260,779	4,491
Rebound:			
1. Guerra and Sancho (2010) - all included in PES			
	UK level:	11%	54%
	Global level:	28%	75%
2.Intermediate: EGWS direct included in PES:			
	UK level:	-5%	45%
	Global level:	12%	68%
3. Turner (2013) - only household direct saving included in PES			
	UK level:	-103%	-25%
	Global level:	-71%	27%

In the Turner (2013) treatment – where only the change in direct household energy use and CO_2 generation that constitute engineering savings directly given by the efficiency improvement are included in PES – net negative rebound in embodied energy and CO_2 remains in all cases except global CO2 generation (where, as explained above, we have the only case where there is a net negative combined multiplier effect in global industrial energy from the reallocation between EGWS and 'Air Transport'). However, the leakage effect is again reflected in a less negative energy rebound.

5. Conclusions

A basic conclusion is that the information set provided by the single rebound measure in Tables 2, 4, 6, and 8 above is limited without the underlying information provided in Tables 1, 3, 5 and 7. Moreover, using the single or inter-regional IO systems detailed in Section 3 it is possible to decompose and 'drill down' further into results that consider industry and spatial distribution of effects. This has not been possible within the space constraints of the current paper (which has a more methodological focus with the scenarios analysed intended to provide only simple numerical examples).

However, rebound, like any ‘indicator’ variable, should be able to provide us with a summary insight into what is going on following an energy efficiency improvement in a given sector of the economy. A key question, then, is do any of the three alternative *illustrative* definitions and their results effectively provide such summary insight to rebound? Our analysis has shown that indirect rebound calculations are highly sensitive – in terms of both magnitude and direction of effect – to what we assume about potential energy savings (PES). Turner (2013) has argued that PES should be based on energy savings actually anticipated by decision makers so that rebound constitutes a measure of how far (or not) an industry or sector has deviated from what was initially expected. The introduction here of consideration of energy use and CO_2 leakage effects through both upstream international supply chains serving UK production, and of direct imports to final (here UK household) consumption spending, adds a further dimension not generally considered in indirect or economy-wide rebound studies. Effective incorporation of this additional dimension in reporting results of rebound studies may add to the information set of interest to different types of policy decision makers at different levels of regional, national and international governance particularly in terms of addressing climate change challenges. However, such an approach emphasises the need for clarity and transparency in what a single rebound measure (even one reported at different spatial levels as in the analysis above) actually can tell us.

Indeed, increasing the level and complexity of effects involved gives pause to consider a wider problem. Here we are only considering indirect re-spending effects as one element of a fuller, economy-wide rebound effect. Demand-driven IO models are useful for focussing on the embodied energy and emissions content of supply chains. Moreover, they are transparent and familiar to many policy analysts. On the other hand, they are limited if we need to consider a fuller set of economic reactions and interactions as nominal prices and incomes start to change in response to an improvement in efficiency in energy or any other input to production or consumption activity. This is why CGE models (incorporating IO databases) have generally been used in studies involving fuller consideration of economy-wide rebound. In doing so we would contend that a crucial question must be what single rebound measures reported in any study actually tell decision-makers (as against general equilibrium modellers)? This would seem to be the necessary central focus of the continuing debate.

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Appendix A: Countries Included in the WIOD Inter-Country Input Output Database.

WIOD Abbreviations	Country
AUS	Australia
AUT	Austria
BEL	Belgium
BRA	Brazil
BGR	Bulgaria
CAN	Canada
CHN	China
CYP	Cyprus
CZE	Czech Republic
DNK	Denmark
EST	Estonia
FIN	Finland
FRA	France
DEU	Germany
GRC	Greece
HUN	Hungary
IND	India
IDN	Indonesia
IRL	Ireland
ITA	Italy
JPN	Japan
KOR	South Korea
LVA	Latvia
LTU	Lithuania
LUX	Luxembourg
MLT	Malta
MEX	Mexico
NLD	Netherlands
POL	Poland
PRT	Portugal
ROU	Romania
RUS	Russia
SVK	Slovakia
SVN	Slovenia
ESP	Spain
SWN	Sweden
TWN	Taiwan
TUR	Turkey
GBR	United Kingdom
USA	United States
ROW	Rest of World

Appendix B: Industrial sectors in the WIOD Industry-by-Industry Inter-Country Input Output Database.

Sector Number	WIOD Sector Codes	Sectors Names	ISIC Rev 3.1
1	AtB	Agriculture, Hunting, Forestry and Fishing	01, 02, 05
2	C	Mining and Quarrying	10, 11, 12,13, 14
3	15t16	Food, Beverages and Tobacco	15, 16
4	17t18	Textiles and Textile Products	17, 18
5	19	Leather, Leather and Footwear	19
6	20	Wood and Products of Wood and Cork	20
7	21t22	Pulp, Paper, Paper , Printing and Publishing	21, 22
8	23	Coke, Refined Petroleum and Nuclear Fuel	23
9	24	Chemicals and Chemical Products	24
10	25	Rubber and Plastics	25
11	26	Other Non-Metallic Mineral	26
12	27t28	Basic Metals and Fabricated Metal	27,28
13	29	Machinery, NEC	29
14	30t33	Electrical and Optical Equipment	30,31,32,33
15	34t3	Transport Equipment	34,35
16	36t37	Manufacturing, NEC; Recycling	36,37
17	E	Electricity, Gas and Water Supply	40,41
18	F	Construction	45
19	50	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	50
20	51	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	51
21	52	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	52
22	H	Hotels and Restaurants	55
23	60	Other Inland Transport	60
24	61	Other Water Transport	61
25	62	Other Air Transport	62
26	63	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	63
27	64	Post and Telecommunications	64
28	J	Financial Intermediation	65,66,67
29	70	Real Estate Activities	70
30	71t74	Renting of Machinery and Equipment and Other Business Activities	71,72,73,74
31	L	Public Admin and Defence; Compulsory Social Security	75
32	M	Education	80
33	N	Health and Social Work	85
34	O	Other Community, Social and Personal Services	90,91,92,93
35	P	Private Households with Employed Persons	95-97

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