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A 'Carbon Saving Multiplier' as an alternative to rebound in considering reduced energy supply chain requirements from energy efficiency?

Karen Turner*, Antonios Katris

Centre for Energy Policy, University of Strathclyde International Public Policy Institute, McCance Building, 16 Richmond Street, Glasgow G1 1XQ, Scotland, UK

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ABSTRACT

A growing area of research into rebound effects from increased energy efficiency involves application of demand-driven input-output models to consider indirect energy consumption effects 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 effects involving energy use and/or carbon emissions in supply chains of both energy and non-energy goods and services have been calculated. We propose that more transparency for policymakers may be introduced by replacing consideration of what are often referred to as 'indirect rebound' effects with a simple Carbon Saving Multiplier metric. We illustrate using results from a demand-driven input-output model that tracks supply chain activity at national and/or global level. We argue that this captures and conveys the same information on quantity adjustments in energy used in supply chain activity but does so in a manner that is more positive, transparent, understandable and useful for a policy audience. This is achieved by focusing (here via carbon emissions) on the net benefits of changes in different types of energy use at both household and supply chain levels when energy efficiency improves in households.

1. Introduction

An interesting area of rebound research has developed in considering the impacts on energy use in supply chains from 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 where a substitution effect involves consumers re-allocating spending from more to less energy-intensive goods or services. However, full consideration of the latter (where energy-intensity of different goods and services depends on energy use at different points of up-stream supply chains), is more commonly undertaken using multi-sector economy-wide rather than purely microeconomic models. In a computable general equilibrium context, Turner (2009) refers to reductions in energy use in the supply chains of energy production sectors faced with reduced demand as efficiency increases as *'negative multiplier effects'*. That is, a reduction in energy demand by a more efficient user triggers further reductions in energy use in the energy supply chain. However, there may also be *positive multiplier effects* on energy use in other supply chains as a result of changing spending decisions and economic expansion following a boost to energy efficiency.

Here we consider how the multiplier concept may be developed to provide a more policy relevant and useful measure than rebound in considering *net* energy saving benefits that may manifest at a wider economy level when efficiency increases in specific energy uses. We argue that the literature on measurement of indirect, and potentially also fuller 'economy-wide' rebound effects has become confusing and misdirected in its focus on defining 'actual' and 'potential' energy savings in a rebound metric. This is particularly the case where the 'potential energy savings' includes more than the autonomous change in energy efficiency for which direct rebound effects are estimated, and 'actual energy savings' includes consideration of additional energy savings elsewhere in the economy (i.e. beyond that of the more efficient energy user). Rather we propose that what policymakers need to know is whether their proposed energy efficiency improvement will reduce overall energy use in the economy. Furthermore, where policymakers are concerned with the climate change impacts of energy use, their concern may be on how changes in energy use translate to carbon emissions and this may extend beyond the boundaries of the national economy where energy efficiency improving measures are introduced.

Understanding the wider energy use implications of increased energy efficiency breaks into two stages. First, to what extent is the

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[*] Corresponding author.
E-mail address: karen.turner@strath.ac.uk (K. Turner).

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targeted energy use reduced; for example, use of gas to heat and provide hot water in homes where more efficient boilers are installed? This requires consideration of any direct rebound that occurs via price and income effects on the household decision regarding how much heat and hot water to use. Second, how does the household decision impact total energy use in the wider economy? In this context, the main policy concern may be in terms of the net impact on carbon emissions (as the varying but main social/public cost of different types of energy use) and whether this adds to or erodes the savings achieved at household level. Additionally, there may be policy concern over the security of different types of energy supply (e.g. international gas supply in Europe and/or renewable vs. non-renewable 'base load' electricity generation capacity). In this context, it is important to understand any unanticipated demand pressures on this supply so that there may be a need to consider different types of energy use at the wider economy level.

This is the type of information that indirect and economy-wide rebound measures may aim to provide (and in the context of industrial energy efficiency in addition to the household example above). However, our proposition is that the lack of policy attention to studies in this area, and the academic debate over rebound calculations beyond direct levels, implies that it a simpler and more transparent metric is required. We propose that the information required can be more simply and transparently delivered by considering simple energy or carbon saving multipliers. In this paper we focus on a 'Carbon Saving Multiplier' (CSM), which is given by the ratio of total carbon savings across the economy to those achieved directly by the more efficient user. The CSM can then be compared across different scenarios with the aim of maximising its value. The carbon focus is motivated by the climate change policy concern noted above and by the need to find a common indicator of the impact of different types of energy across the economy. However, we go on to propose that, where different types of energy use can be identified and tracked at the appropriate sectoral and geo-political level, it would be relatively straightforward to adapt and apply the proposed multiplier metric accordingly.

For the purpose of simplifying the proposition and argument at this stage, we consider a very straightforward case where an autonomous increase in efficiency in household energy use has been achieved (i.e. abstracting from any change in technology involved), under different assumptions regarding any direct rebound in household energy use. We focus attention of quantity adjustments (in production of output and associated energy use) in energy and non-energy supply chains in response to changes in patterns of household spending. This permits the application of a simple demand-driven input-output (IO) model to measure impacts of changes in supply chain activity on net energy-related carbon emissions across the economy and to compute the CSM. However, the paper concludes by considering how the proposed multiplier metric could be applied in a fuller general equilibrium analysis of a wider set of market responses (impacting incomes, prices and quantities) to increased energy efficiency in any (production or consumption) sector of the economy.

The remainder of the paper is structured as follows. In Section 2 we review in more detail the literature that has to date considered supply chain energy use in terms of 'indirect' or 're-spending' rebound effects and elaborate the argument that a multiplier metric such as the CSM may offer a more policy relevant and useful alternative in considering rebound pressure beyond the level of direct rebound in the more efficient user's own energy use. In Section 3 we present the inter-regional IO method used to calculate and decompose the CSM. In Section 4 we apply this method to a simple example of a 'what if' scenario of re-spending by UK households following an efficiency improvement in their use of electricity and gas. Conclusions – including potential further development of the proposed multiplier metric - and policy implications are drawn in Section 5.

2. The problem: should supply chain energy use be considered as part of the rebound effect?

The issues around consideration of indirect and economy-wide rebound effects extend beyond our focus in this paper on energy use and associated carbon emissions in supply chains, and beyond examining the impacts of increased efficiency in household energy use. The extensive literature on wider indirect and economy-wide rebound studies of impacts of increased efficiency in consumptive or productive energy use is reviewed in publications such as Sorrell (2007), Turner (2013) and Madlener and Turner (2016). Moreover, as noted above, the concept of (negative) multiplier effects in energy supply and how this may impact economy-wide rebound estimates in a full general equilibrium analysis, has been introduced by Turner (2009).

However, explicit consideration of multiplier relationships and effects is most familiar in the context of input-output (hereafter IO) modelling. The conventional demand-driven IO model (Leontief, 1936; Miller and Blair, 2009) is a simple linear economy-wide framework that generally limits attention to quantity adjustments in up-stream supply chains in response to changes in demand by the final consumers of goods and services produced in the economy. Despite the limitations given by its simplifying assumptions, many policy analysts are familiar with the use of multipliers derived using a demand-driven IO model (e.g. how many jobs are likely to be created throughout the economy for each job directly supported by a given investment?). On this basis, the initial proposition made in this paper - that a multiplier metric may replace calculation of rebound beyond the direct level - is set in an IO rather than a fuller general equilibrium context. Nonetheless, as noted above, we do return to consideration of wider application of the metric in the final section of the paper.

Analysis using demand-driven IO models is being increasingly commonly used to examine what have been referred to as indirect 're-spending' rebound effects (Sorrell, 2009). It tends to focus on energy used and/or pollution generated in supply-chains impacted when spending on goods and services changes in response to increased efficiency in household energy use. See, for example, Chitnis et al. (2013, 2014), Druckman et al. (2011), Freire-Gonzales (2011), Lecca et al. (2014), Lin and Du (2015), Pfaff and Sartorius (2015) and Thomas and Azevedo (2013a, 2013b).

A crucial point is that, while all these IO studies implicitly use multipliers to calculate their results – with Leontief's (1936) inverse or multiplier matrix constituting the core mechanism of the IO model (see Miller and Blair, 2009) – they tend not to explicitly report results in terms of multiplier relationships. However, particularly given the familiarity of many policy communities, a simple extension of the basic IO multiplier concept may constitute a useful indicator of the impact of pressures on wider energy uses that have come to be referred to indirect rebound effects, but may be more strictly referred to as indirect energy consumption effects.[1] Moreover, this may be preferable to reporting the 'rebound effect' itself, which may be subject to policy resistance due to its inherently negative perspective (by focussing on what we do not rather than what we do achieve in terms of energy savings) and a lack of consistency and comparability of rebound calculations made using IO modelling results.

To explain the latter point, we note that some of the studies listed above report (partly depending on the specific scenario modelled) very large indirect rebound effects associated with supply chain energy use

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[1] We suggest this change in terminology because what we refer to as the calculated indirect energy consumption effects are a consequence of the net effect of (a) primary energy savings due to the autonomous chance in energy efficiency *and* (b) the consumer's direct rebound effect (i.e. the effect that determines the magnitude of reduced energy expenditures linked to the affected technology and thus the purchase of other energy and non-energy services). We are grateful to an anonymous reviewer for making this clarification.

affected by household re-spending decisions. On the other hand, Lecca et al. (2014) report this element to be negative, noting (in their UK-focussed analysis) that reduced energy use in the supply chains of energy producers more than off-sets increases in the (less energy-intensive) supply chains of goods and services where spending is reallocated.

The key point to note is that the cause of such a qualitative difference in results is not limited to the scenarios modelled. Rather, there is disagreement in the literature over how negative multiplier effects in energy sector supply chains enter the rebound calculation. The problem is that most indirect (and economy-wide) rebound studies explicitly or implicitly define rebound in terms of the ratio between ‘actual energy savings’ (AES) and ‘potential energy savings’:

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

However, there is a lack of consistency over what different studies consider within AES and PES when the rebound effect is considered at an indirect or economy-wide level (see Guerra and Sancho, 2010; Turner, 2013). A crucial issue is how quantity adjustments in use of energy by energy producers to produce output that is no longer required (when demand falls with increased efficiency) should be treated. Guerra and Sancho (2010) argue that this should be incorporated into PES while Turner (2013) argues that it should be reflected in AES. Applied studies have then gone on to explicitly or implicitly follow one approach or the other. For example, in studies of re-spending decisions following increased energy efficiency in UK households, Druckman et al. (2011) adopt the Guerra/Sancho approach while Lecca et al. (2014), follow Turner (2013).

The purpose of the current paper is not to consider the relative merits of these alternative approaches to calculate ‘indirect’ or ‘re-spending’ rebound. Rather, we argue that the lack of clarity in exactly how rebound is calculated in these types of studies - particularly, but not exclusively in terms of the treatment of quantity adjustments in energy supply - adds to a set of barriers that prevent policy attention to rebound research findings. Reporting of what may seem to be a standard rebound calculation (based on Eq. (1)) has become controversial and is often not well received by policy audiences.

Moreover, in the context of the discussion above, problems of transparency and also the relationship with rebound, as defined in earlier works such as Greening et al. (2000), arise. This is particularly the case as the focus of rebound research has extended beyond the basic demand response by a more efficient user as the cost of the relevant energy service and, thus, real income changes. The complexity of the economic response increases as we focus attention beyond the more efficient user's response to the change in the price of the relevant energy service delivered and so do the determinants of rebound. Thus, there is a question in terms of transparency and clarity in how more levels and types of effects are introduced to rebound calculations and how results are reported.

The objective of the remainder of this paper is to attempt to introduce some transparency and clarity to the treatment of indirect energy consumption effects through re-spending using a simple multiplier metric. As noted, above, the primary motivation for this is that many policy analysts are familiar with use of the demand-driven IO 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 a simple sample scenario of an energy saving realised and potential re-spending decision – to begin by identifying and applying what we distinguish as *computational multipliers*. These are the system multipliers from (3) that relate emissions generated to a monetary amount of spend and which allow us to generate an information set on the potential changes in energy-related carbon emissions due to re-spending effects. We then demonstrate how reporting of a simple ‘Carbon Saving Multiplier’ (CSM), which is a *results multiplier* that relates computed energy-related supply chain emissions estimates to the household emissions directly associated with the monetary spend.[2] Our argument is that this may give a more consistent and straightforward set of information than an extended rebound metric. This is by focussing on the additional net carbon savings that may be anticipated via supply chain interactions and setting these relative to initial direct savings at this level of the more efficiency energy user:

$$CSM = \frac{Direct\ plus\ supply\ chain\ carbon\ savings}{Direct\ carbon\ savings} \tag{2a}$$

Given that direct carbon savings appear in both the numerator and denominator of (2a), the CSM can also be stated as

$$CSM = 1 + \frac{Supply\ chain\ carbon\ savings}{Direct\ carbon\ savings} \tag{2b}$$

This means we are referring to additional supply chain savings (e.g. kilotonnes) realised per unit (kilotonne) of direct carbon savings by the more efficient user. In scenarios where supply chain carbon emissions fall (particularly energy supply chain emissions as demand for energy falls), the CSM will be positive. In scenarios where supply chain emissions rise (e.g. where savings on energy spending are reallocated to other goods and services), and the increase in supply chain emissions is larger than the decrease in direct emissions, it will be negative. However, for any scenario of re-spending (i.e. spending shifting away from energy and towards other goods and services), it may be more informative to first calculate the CSM for the full energy supply chain impacts of reduced spending, and then consider how it is eroded when the supply chain impacts of the reallocation of spending are added to the numerator of (2). Note that if policy interest lies in one or more of the underlying energy uses the ‘savings multiplier’ in (2) could be stated as an Energy Savings Multiplier.

3. Inter-regional input-output multiplier method for analysing the implications of energy use in supply chains

In this section we derive the demand-driven input-output model used to calculate the CSM for some simple numerical examples. As noted above, given the importance of the increasingly international nature of supply chain activity for climate policy concerns, we focus our attention on the inter-regional input-output (IRIO) model (Miller and Blair, 2009; Turner et al., 2007; Wiedmann, 2009) and apply it using global inter-country input-output data. This facilitates consideration of energy-related carbon impacts at an industrial level in regions/countries other than that where energy efficiency actually increases. This may be important, for example, where reductions in emissions linked to energy supply chain activity at home may occur in a context of increased non-energy supply chain emissions abroad. The multi-country spatial focus introduced here is a relatively novel development in the rebound literature more generally, where indirect and economy-wide rebound studies have tended to focus on impacts on energy use within a given regional or national economy.[3,4]

Consider a global economy where we have r,s=1,….,T producing and consuming regions/countries, each with i,j=1,….,N industries/

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[2] The CSM as results multiplier that relates total CO2 emissions to CO2 directly emitted by households is what policy analysts may refer to simply as an emissions multiplier. On the other hand, the computational output-CO2 multiplier may be referred to as ‘CO2 effects’. See policy language used by Scottish Government to refer to analogous employment multipliers at http://www.gov.scot/Topics/Statistics/Browse/Economy/Input-Output/Mulitipliers.

[3] Economy-wide rebound is considered in a global inter-regional context in a CGE analysis of increased energy efficiency in German industries by Koesler et al. (2016). This analysis also uses the WIOD database (as the core database describing economic structure in the CGE model) as used below for our IO analysis.

[4] For readers more interested in single region/nation analysis please see Turner and Katris (2015) for the analogous single region exposition.

outputs, the central element of the demand driven IO model is a multiplier matrix, *EL*

$$EL(global)=\begin{bmatrix} e_i^1 b_{ij}^{11} & \cdots & e_i^1 b_{ij}^{1s} & \cdots & e_i^1 b_{iN}^{1T} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_i^r b_{ij}^{r1} & \cdots & e_i^r b_{ij}^{rs} & \cdots & e_i^r b_{iN}^{rT} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_N^T b_{Nj}^{T1} & \cdots & e_N^T b_{Nj}^{Ts} & \cdots & e_N^T b_{NN}^{TT} \end{bmatrix} \quad (3)$$

where the component E matrix is a diagonal matrix of sectoral emissions intensities and L is the economic input-output multiplier matrix (often referred to as the Leontief Inverse). Within each element of *EL*, $e_i^r b_{ij}^{rs}$, e_i^r is an element of the diagonal matrix E, denoting the *physical* amount of energy-related carbon emissions (e.g. kilotonnes) generated by industry i in region r in producing one *monetary* unit (e.g. $million) of output. Note that the e_i^r element could be stated for total or different types of physical energy uses or different pollutants. Each element b_{ij}^{rs} of the component L matrix denotes the total amount of output (in monetary or value terms) from industry i in region r that is required to support production of one unit of output j demanded by final consumers in region s. Thus, in applying physical emissions intensities via matrix E, the column total of (3) for any commodity output j demanded by final consumers across all regions s, tells us the total amount of carbon emissions generated in supply chain activity to meet one monetary unit of that final demand for that output. Each of the column totals of (3) is referred to as the output-emissions multiplier for the commodity output in question.

Final demand is introduced via the (NxT)x(NxT) diagonal matrix of final demand, where we can examine total final demands (in the same monetary units as output) or focus on any one of z=1,...,Z types of final consumer in each country (which, in a global inter-regional framework,[5] will generally include total households, government and capital formation to give us Z=3, although each of these may be further disaggregated, depending on data availability) . We can assess the impact of changes in (exogenously determined) final demands by extending (3) to state $EL\Delta Y$:

$$EL\Delta Y(global)=\begin{bmatrix} e_i^1 b_{ij}^{11}\,\Delta y_{jz}^1 & \cdots & e_i^1 b_{ij}^{1s}\,\Delta y_{jz}^s & \cdots & e_i^1 b_{iN}^{1T}\,\Delta y_{Nz}^T \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_i^r b_{ij}^{r1}\,\Delta y_{jz}^1 & \cdots & e_i^r b_{ij}^{rs}\,\Delta y_{jz}^s & \cdots & e_i^r b_{iN}^{rT}\,\Delta y_{Nz}^T \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_N^T b_{Nj}^{T1}\,\Delta y_{jz}^1 & \cdots & e_N^T b_{Nj}^{Ts}\,\Delta y_{jz}^s & \cdots & e_N^T b_{NN}^{TT}\,\Delta y_{Nz}^T \end{bmatrix} \quad (4)$$

Use of (4) and the underlying output-emissions multiplier matrix in (3) – or results for elements thereof – allows us to consider impacts of a change in a particular type of final consumption demand (e.g. z=household expenditure) for the outputs of any sector j (e.g. electricity and/or gas supply) in any region s (e.g. UK) on emissions in any sector i in any producing region r (where $r \neq s$ means a direct import from another country). The main diagonal of sub-matrices in each (3) and (4) (i.e. where r=s) gives us own-country emissions impacts of domestic final consumption. The off-diagonal sub-matrices then give us impacts of spending by final consumers on domestic or imported goods where emissions impacts occur in other regions (i.e. where the final consumption activity and emissions impact are in different countries).

In this way, the system in (4) provides information on changes in physical supply chain emissions (or energy use if that is the focus of the specification of the E matrix) that could be used to calculate indirect or re-spending rebound effects – using one of the contested methods argued by Guerra and Sancho (2010) and Turner (2013) – at different spatial scales.

However, here we focus our attention instead on using the results from the output-emissions multiplier system above to calculate the CSM for different scenarios involving re-spending decisions following an increase in energy efficiency by final consumers of goods and services.[6] $EL\Delta Y$ is computed for the stages of reduced spending on the output of energy supply sectors followed by any re-spending on one or more commodity outputs, j, of different production sector(s) at home and abroad. The results are used to inform the 'supply chain carbon savings' element of equation (2). The IO model is not used to compute the direct carbon savings (within the household final consumption sector) that also inform the CSM. Instead, these should be drawn from appropriate direct rebound studies of the impacts of increased energy efficiency on the more efficient energy use. That is, the CSM and IO system in (2)–(4) above add *additional* but very policy relevant information on the wider net energy saving benefits of an energy efficiency initiative. This is information that is not captured by, and therefore complements and supplements direct rebound estimates.

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 inter-regional IO accounts reported as part of the World Input-Output Database (WIOD) project (Timmer et al., 2015) to calculate the components underlying Eq. (4).[7] This version of 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 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. Please note that only CO2 emissions are related to specific energy uses for households (other GHG are not), with the implication that we only calculate carbon emissions for CO2. This means that total supply chain emissions and the CSM are considered for the same pollutant as we can determine direct emissions reductions within the household sector; however, a fuller accounting of the carbon impacts of changes in energy use would ideally require that all GHG be included.

It is important to note that the complex process of constructing global inter-regional IO 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. – means that sacrifices have to be made particularly in terms of industry level detail/sectoral disaggregation. This may be problematic in terms of accuracy of multipliers computed (Lenzen et al., 2004).[8] A key problem area in considering both energy use and related emissions within supply chains using the WIOD database is the

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[5] In a national IO framework exports to production sectors/industries in other countries will be reported as final demands (from the perspective of the producing nation). However, in a global inter-regional IO framework, these are endogenised in the *EL* multiplier matrix.

[6] In an earlier working paper version of the current paper, we do calculate indirect energy consumption effects in terms of underlying energy uses and CO2 emissions using IO modelling results, and do so for both the Guerra/Sancho and Turner methods. See Turner and Katris (2015)

[7] The WIOD database can be accessed at http://www.wiod.org/release13. Here we use the 2009 IRIO table that can be downloaded at http://www.wiod.org/database/wiots13 and corresponding 'CO2 emissions' data (limited to CO2 emissions from energy use) for each country at http://www.wiod.org/database/eas13 that allow to construct E for CO2 emissions respectively.

[8] The problem of over-aggregation of industrial activities is a general one across the limited range of global inter-regional databases available for IRIO analyses. For example, the evolving OECD inter-country 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 the focus of sectoral level detail being largely centred on 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.

aggregation of Electricity, Gas and Water Supply in a single industry (although, as noted above, the data do permit identification of emissions within the household sector that are directly related to the gas purchases from this 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 IO method and calculation of the CSM metric proposed 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 output-emissions multipliers, or more correctly (in the current analysis) the output-CO2 multiplier extracted from computing Eq. (3), to examine the composition of emissions generated throughout the supply chain to meet $1 million of final demand for the output of j=EGWS, focussing on the r=UK sector. We then estimate the reduction in CO2 emissions within the EGWS supply chain in response to reduced energy spending by households resulting from a simple energy efficiency improvement where 10% less physical energy is required to deliver the same consumption level. We begin by assuming that this translates to a 10% reduction in UK household spending on EGWS. That is, there is zero direct rebound. We then scale the change in energy spending to different illustrative assumptions about the size of direct rebound effect (that is, as explained in Section 3, we make no attempt to estimate the direct rebound itself).

In Section 4.3 we then consider a very simple illustrative scenario of how spending may be reallocated (i.e. to give a corresponding positive change in y in calculation of (4)). The specification of the re-spend scenario is made simple by focussing on reallocation to a single good/service. This is in order to aid transparency in the proposed CSM metric. We draw on information provided by Chitnis et al. (2013) to identify UK household spending on eating out (which, in our IO system, would involve spending in UK 'Hotels and Restaurants') as a good/service with a relatively high income elasticity for UK households as a potential target for reallocation of spending.[9]

4.2. Target of energy efficiency improvement: UK household use of and spending on outputs of the UK 'Electricity, Gas and Water Supply' industry

In the WIOD database for 2009, UK households are recorded as spending $55,258 m (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 involves use of 1526 PJ (petajoules), which in turn incorporates 1085 PJ of electricity and 441 PJ of natural gas. Only the use of natural gas causes any CO2 emissions to be directly generated *within* the UK household sector, which the WIOD data report as 61,716 kt (kilotonnes).

This is the direct energy use that would be the subject of any efficiency improvement in how households use energy within their homes. 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, there is a potential direct engineering energy saving of 152.6 PJ. In the absence of any direct rebound, this would translate to a 10% reduction in household final demand spending on EGWS output. The potential direct energy saving of 152.6 PJ is associated with a reduction of 6172 kt of CO2 directly emitted by households. In the analysis below, we consider how this direct CO2 saving and the related reduction in spending on EGWS outputs is impacted by different assumptions about the possible extent of direct rebound effects. Throughout, for reasons of simplicity, we abstract from any investment activity that may be involved in introducing the efficiency improvement.

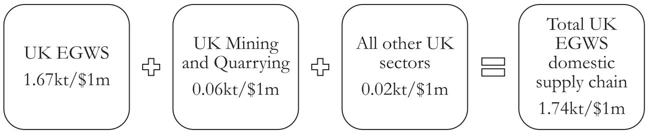

Fig. 1. Key components of UK EGWS domestic output-CO2 supply chain multiplier (kilotonnes/$1 m).

When we calculate the inter-regional output-CO2 multiplier matrix using (3), the column total for j=EGWS and s=UK is 1.89. This tells us that, for every $1 m of final demand expenditure by UK households (or other final consumers) for the output of the EGWS sector, 1.89 kt of carbon emissions are generated throughout the global supply chain of this sector.

Within the element of this column where i=j=EGWS and r=s=UK (i.e. own-sector emissions) we have emissions generated within EGWS itself of 1.67 kt. This equates to 88% of the total. A further 0.08 kt (just over 4% of the total) is located elsewhere in the UK supply chain. The bulk of this, 0.06 kt (or 3.3% of the total 1.89 multiplier) is in the j=Mining and Quarrying sector (which includes the UK 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-CO2 multiplier, which gives us just over 92%, or 1.74 kt, of the 1.89 kt total. See Fig. 1 for a simple summary illustration.

The other 8%, 0.15 kt of CO2 emissions generated per $1 m output to meet final demand for EGWS is located overseas and given by summing down the $r \neq s$ entries of the column in (3). Again, this can be decomposed in terms of which industries in which country (or counties) emissions in the EGWS supply chain are located. The largest shares of the 0.15 kt external effect are located in the composite ROW region (0.08 kt or 57% of the overseas emissions, 4.5% of the total multiplier) and Russia (0.03 kt or 18% and 1.5%).[10] Within both Russian and the composite ROW regions the two largest shares of emissions are located in those countries' EGWS sectors (most likely gas supply) and in 'Mining and Quarrying'. However, there are also notable impacts in other, mainly petroleum refining, metal manufacture and transport, activities.

Figs. 1 and 2 summarise the key elements of the UK EGWS output-CO2 multiplier. The key point to note is that the bulk of CO2 emissions generation in the UK EGWS global supply chain is in fact located within the UK, and most of that involves own-sector emissions.

Now let us consider how the output-CO2 multiplier (calculated using (3)) determines the gross CO2 impacts of the $5526 m reduction in UK household final consumption spending on EGWS that would be associated with a 10% increase in efficiency in the use of electricity, gas and water in the absence of any direct rebound effect. We calculate this using (4). For simplicity, given that the UK household spending on EGWS is almost entirely domestic, we will assume that reduced energy

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[9] We use income elasticity data on the basis that we are looking at a reallocation of spending that results from real income savings. That is, households are better off in real terms as the cost of energy services facilitated by gas and electricity use falls with an efficiency improvement.

[10] 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.

Fig. 2. Key components of UK EGWS overseas output-CO2 supply chain multiplier (kilotonnes/$1 m).

Table 1
Changes in CO2 emissions associated with a decreased spending in UK household use of UK EGWS outputs following a 10% energy efficiency improvement.

	No direct rebound	10% direct rebound	50% direct rebound
Reduction in monetary spend on UK EGWS outputs ($million)	−5525.8	−4973.2	−2762.9
	Change in CO2 emissions (kilotonnes)		
A. Reduction in direct CO2 emitted by UK households	−6172	−5554	−3086
Reductions in CO2 emissions in UK EGWS supply chains:			
Total multiplier effect per $1 m *spend:*	*1.89*	*1.89*	*1.89*
B. Emissions in UK EGWS sector (1.67 kt per $1 m)	−9202	−8282	−4601
C. Emissions in other UK industries (0.08 kt per $1 m)	−422	−380	−211
Sub-total UK	**−9624**	**−8662**	**−4812**
D. Emissions in all overseas industries (0.15 kt per $1 m)	−829	−746	−414
Global total	**−10,453**	**−9,408**	**−5227**
Total reduction in UK CO2 emissions	**−15,796**	**−14,216**	**−7898**
Total reduction in global CO2 emissions	**−16,625**	**−14,962**	**−8312**
Carbon Saving Multiplier (UK level)	**2.56**	**2.56**	**2.56**
Carbon Saving Multiplier (Global level)	**2.69**	**2.69**	**2.69**

spending is experienced only in this sector. This means that there will only be one entry – Δy^{s}_{jz} where j=EGWS, z=households and s=UK – in the inter-regional variant of the diagonal Y matrix that is post-multiplied to the output-CO2 multiplier matrix (3) to give us the results of the shock via Eq. (4). Again, 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. It also means that the results reported in the first numerical column of Table 1 can be computed by simply applying the UK EGWS output-CO2 multiplier (1.89) and/or its component column entries from (3) in a simple off-line multiplications with the $5526 m reduction in demand for that sector's output (i.e. without any direct rebound).

In the second numerical row of the table we begin by reporting direct reduction in household CO2 emissions (6172 kt) associated with the 10% efficiency improvement in the absence of direct rebound that accompanies the $5526 m reduction in EGWS spending. As explained in Section 3, this item – labelled A – would be computed outside of the IO analysis, with the estimation of supply chain effects (calculated using the IO model) then added to give the total change in CO2 emissions to inform the CSM in (2).

In the third row of Table 1 we report the total output-CO2 computational multiplier (column total of (3) for UK EGWS). As noted above, this may be multiplied by the direct shock of value of $5525.8 m to give the total change (reduction) in global CO2 emissions to produce 'Global total' result in the eighth numerical row. However, in rows 4–7 on Table 1, we also report the key components of the overall multiplier values as items B-D (reporting the relevant component elements of the output-CO2 multiplier within the label of each row). This allows us to distinguish different aggregate level industry sources of emissions generated 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 a more detailed analysis.

However, for our purposes here, the key point is that the initial reduction in household CO2 emissions (abstracting from any direct rebound effect in the first column results) from the 10% efficiency improvement in electricity, gas and water use is accompanied by reductions in CO2 emissions throughout the EGWS supply chain. Moreover, given the CO2-intensity of this supply chain (particularly at own-sector level within UK EGWS), these additional reductions are substantial relative to the direct change in household energy use. This is reflected in the ratio of the total UK and global reductions to the reduction in CO2 emitted directly by households that we report in the last two rows of Table 1. This is what we label as the 'Carbon Savings Multiplier'. As explained via equation (2b), the CSM value of 2.69 (Global level) indicates that for every kt of CO2 directly saved by more energy efficient households, a further 1.69 kt is saved in the global supply chain of the UK EGWS sector.

In the second and third numerical columns of Table 1 we have also inserted results where we assume that there is some direct rebound (10% or 50%) that decreases (a) the direct household CO2 emissions savings, and, thus (b) the reduction in spending on the output of the UK EGWS sector that supplies the physical energy used. The main observation that can be made in examining these hypothetical direct rebound scenarios is that, while there is a clear reduction in the CO2 emissions savings, both within the UK and globally, the CSM remains the same. It is important to note that this is a function of IO modelling focus on quantity adjustments in supply chain activity in response to shifts in demand. In a more sophisticated general equilibrium analysis, where nominal incomes and prices may change as a result of the efficiency improvement, it is possible that the CSM value would change for different levels of direct rebound.

4.3. Household re-spending decision: eating out in UK 'Hotels and Restaurants'

We now turn our attention to a simple example of a potential re-spending decision. A basic prediction can be made that, unless the supply chains of any goods/services that spending is redirected towards are more CO2-intensive than that of the energy supply sector where demand is reduced (here UK EGWS), a net reduction in global (industrial) CO2 emissions will occur.

In practice, a scenario where UK households make decisions on reallocating spending saved as their energy efficiency improves 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 simple 'one for one' substitution. We consider a case where the $5526 m (or smaller

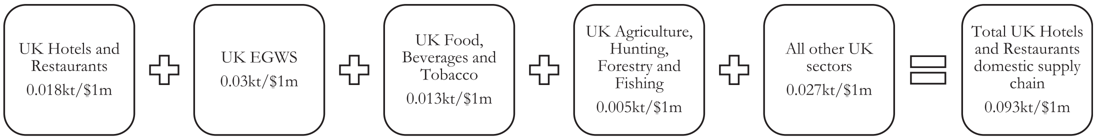

Fig. 3. Key components of UK 'Hotels and Restaurants' domestic output-CO2 supply chain multiplier (kilotonnes/$1 m).

Fig. 4. Key sectors in UK 'Hotels and Restaurants' overseas output-CO2 supply chain multiplier (tonnes/$1 m).

Table 2
Changes in CO2 emissions associated with re-spending of monetary savings to UK 'Hotels and Restaurants' (HR).

	No direct rebound	10% direct rebound	50% direct rebound
Increases in CO2 emissions in UK Hotels and Restaurants supply chain:			
Total multiplier effect per $1 m *spend:*	*0.14*	*0.14*	*0.14*
E. Emissions in UK HR sector (0.0.02 kt per $1 m)	101	91	50
F. Emissions in other UK industries (0.07 kt per $1 m)	413	372	207
Sub-total UK	**514**	**463**	**257**
G. Emissions in all overseas industries (0.05 kt per $1 m)	279	251	140
Global total	**794**	**714**	**397**
Net increase/decrease in UK and global CO2 emissions:			
Change in direct CO2 emitted by UK households (A)	−6172	−5554	−3086
EGWS shock – change in total UK EGWS CO2 emissions (B)	−9202	−8282	−4601
Change in CO2 emissions of all other UK industries (C, E, F)	92	83	46
Net at UK level	**−15,282**	**−13,753**	**−7641**
Change in CO2 emissions outside of UK (D and G)	−550	−495	−275
Net at global level	**−15,831**	**−14,248**	**−7916**
Carbon Saving Multiplier (UK level)	**2.48**	**2.48**	**2.48**
Carbon Saving Multiplier (Global level)	**2.57**	**2.57**	**2.57**

amount where we have some direct rebound) is reallocated from spend on UK EGWS in favour of outputs of the UK 'Hotels and Restaurants' sector. As noted above, this target for reallocation is motivated (but not quantified) 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 energy, is also motivated by the fact that (again according to the WIOD 2009 data) the bulk, 95%, of UK household spending on 'Hotels and Restaurants' is in the domestic sector.

As in Section 4.2 for EGWS, we extract information on the output-CO2 emissions multiplier from the matrix calculated using (3). The column total of (3) for j=Hotels and Restaurants and s=UK takes the value of 0.14. This tells us that for every $1 m of final demand expenditure by UK households (or other final consumers) 0.14 kt of CO2 are generated throughout the global supply chain of the UK 'Hotels and Restaurants' sector.

The first thing to note is that the output-CO2 multiplier for this type of spend is considerably lower than the 1.89 kt per $1 m that household spending has been reallocated away from. Therefore, we clearly expect a net negative impact on total global CO2 emissions. However, it is important to consider how the nature the global supply chain (and thus the composition of the output-CO2 multiplier) for the UK 'Hotels and Restaurants' multipliers differs from that of the UK EGWS sector.

First, own-sector CO2 emissions in UK 'Hotels and Restaurants' are much less important in contributing to the total global multiplier than found above for the case of UK EGWS. Detailed analysis of the j= Hotels and Restaurants, s=UK column of the matrix calculated from (3) reveals that 52%, or 0.07 kt of the 0.14 kt total are CO2 emissions generated by all the other UK supply chain sectors. See Fig. 3. The largest contributor to this is 0.03 kt per $1 m generated in the UK EGWS sector (equating to just 19% of the total global multiplier). The other two main contributors in the UK supply chain are CO2 emissions by the 'Agriculture, Hunting, Forestry and Fishing' sector (0.005 kt per $1 m) and 'Food, Beverage and Tobacco' (0.013 kt).

In terms of the 35% of the global multiplier value involving CO2 emissions in overseas production, this is spread across multiple countries and industries. In terms of the types of industries where overseas CO2 emissions are generated, there are similarities with the composition of the UK supply chain in terms of the importance of emissions within agricultural, food and drink and EGWS industries. However, transport activities and a number of manufacturing activities[11] play a more important role in the overseas supply chain than they do within the UK. See Fig. 4 (please note that this is reported in tonnes rather than kilotonnes given the small quantities involved).

The difference in composition of domestic and international supply chains is a key issue motivating the use of the inter-regional IO model. In Section 3 we have explained that use of this type of model facilitates consideration of energy-related CO2 oimpacts of increased energy efficiency in one county at an industrial level in others. We have argued that this may be important if reductions in emissions linked to energy supply chain activity at home occur in a context of increased non-energy supply chain emissions abroad. This does prove to be important even in the simple re-spending scenario considered here. While the results in Table 2 show that the reallocation of UK household spending between UK EGWS and UK 'Hotels and Restaurants' does

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[11] In Fig. 4 'Basic Metals and Fabricated Metals' is identified as an up-stream overseas industry where a relatively high level of CO2 emissions are required per $1million of final demand for the output of UK 'Hotels and Restaurants'. This will be related to equipment needs throughout the supply chain (including transportation).

result in a global net reduction of CO2 emissions, this is mainly driven by the decrease within UK households and the domestic EGWS industry.

We would note that detailed analysis of the results of computing the model in (4) reveals that there are sixteen nations, fourteen of which are EU trade partners, where net increases in CO2 emissions occur. The largest contribution is through CO2 generation in the Dutch, French and Indian agricultural, food/beverage and transportation industries. While the net country and industry level increases are relatively small in magnitude, two key points can be made. First, actions to increase energy efficiency and reduce emissions within the UK may lead to increased supply chain emissions elsewhere. Second, it is use of the inter-country modelling framework that allows us to locate and consider any gross increases in emissions that may otherwise be masked within headline results for net impacts.

More generally, in the top half of Table 2 we report the results of the increased spending in UK 'Hotels and Restaurants' (for the 0, 10 and 50% direct rebound cases), again decomposing the multiplier calculations to consider different elements of the impact within and outside of the UK. We label these E–G to follow on from the items A–D identified for the reduction in UK EGWS spend in Table 1. Then, in the bottom half of Table 2 we bring the corresponding elements together to report the net impacts on CO2 emissions within and outside the UK resulting from the reallocation of spending.

Again, in the final two rows on Table 2 we report the CSM for the full reallocation of spending. The key point to note is that the CSM is eroded relative to the results reported in Table 1 for the reduced energy spending alone. This is due to the increases in CO2 emissions in the UK 'Hotels and Restaurants' supply chain reported in the top half of Table 2. Moreover, note that the erosion of the CSM at global level (a 4% reduction from 2.69 to 2.57) is slightly greater than that at UK level (a 3% reduction from 2.56 to 2.48). Finally, note once again that the CSM does not change when we assume different levels of direct rebound. However, we remind the reader that this is determined by the IO focus on quantity adjustments and may not hold in a more sophisticated general equilibrium analysis of a fuller range of economy-wide responses.

5. Conclusion and policy implications

This paper has developed the proposition that more transparency in research findings to inform policymakers concerned with the wider impacts of energy efficiency improvements may be introduced by replacing consideration of rebound beyond direct level with a simple Carbon Saving Multiplier (CSM) metric. We have done so using illustrative results from a demand-driven inter-country input-output model that tracks supply chain activity at national and/or global level. We have demonstrated that the CSM approach captures and conveys the same information on quantity adjustments in energy used in supply chain activity as in many indirect 're-spending' rebound studies. However, we have argued that the CSM approach does so in a manner that is more positive, transparent, understandable and useful for a policy audience given its focus on the net benefits (represented by resulting CO2 emissions) of changes in different types of energy use at both household and supply chain levels when household energy efficiency improves. Moreover, we have demonstrated how decomposition of the input-output multiplier results permits identification of any gross increases in emissions in different industries and/or countries in the up-stream supply chains of goods and services where spending facilitated by energy savings may be reallocated.

In summary, the proposed CSM method provides a policy relevant approach that complements and supplements information provided by studies of direct rebound effects in the energy use of more efficient users. It is one that, if applied effectively with clear communication of results, may deliver a step increase in policy attention to and impact from consideration of the wider pressures on energy use and associated impacts that may result from the economic responses to increased energy efficiency. Moreover, the 'savings multiplier' concept may be straightforwardly applied to variables of interest other than CO2 – e.g. different types of energy use, other types of pollution, or other physical resource uses – where appropriate data are available.

However, we have drawn attention to the trade-off between employing input-output as a relatively simple multi-sector economy-wide modelling framework that many policy analysts are familiar with and the implications of the restrictive assumptions involved. It has been extensively argued in the literature that more flexible and theory consistent general equilibrium frameworks (which incorporate input-output databases but introduce consideration of changes in prices and incomes in multiple sectors and markets) may provide a more informative modelling approach to analysing and measuring the wider impacts of increased energy efficiency at sectoral level. However, the CSM metric remains relevant: in this paper the input-output approach is simply used to quantify supply chain savings as an input to the CSM. This input could be quantified using, for example, a CGE modelling framework, which would also permit extension of exactly what is considered as part of the multiplier effects. That is, a fuller set of economy-wide (domestic and international) impacts may be captured in the Carbon and/or Energy Saving Multiplier metric using more sophisticated modelling techniques. However, the input-output approach remains, at the very least, a useful pedagogic tool in conveying and developing the fundamental usefulness and policy relevance of adopting a simple multiplier approach to communicate the net impacts of what may be very complex economic interactions following an increase in energy efficiency.

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Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2016.12.057.

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