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International spillover and rebound effects from increased energy efficiency in Germany

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ABSTRACT

The pollution/energy leakage literature raises the concern that policies implemented in one country, such as a carbon tax or tight energy restrictions, might simply result in the reallocation of energy use to other countries. This paper addresses these concerns in the context of policies to increase energy efficiency, rather than direct action to reduce energy use. Using a global CGE simulation model, we extend the analyses of 'economy-wide' rebound from the national focus of previous studies to incorporate international spill-over effects from trade in goods and services. Our focus is to investigate whether these effects have the potential to increase or reduce the overall (global) rebound of local energy efficiency improvements. In the case we consider, increased energy efficiency in German production generates changes in comparative advantage that produce negative leakage effects, thereby actually rendering global rebound less than national rebound.

1. Introduction

The pollution/energy leakage literature raises the concern that policies implemented in one country, such as a carbon tax or tight energy restrictions, might simply result in the reallocation of energy use to other countries (Babiker, 2005; Böhringer and Löschel, 2006; Löschel and Otto, 2009; Elliot et al., 2010). This paper addresses these concerns in the context of policies to increase energy efficiency, rather than direct action to reduce energy use. It focusses on measures of the rebound effect.

Improvements in energy efficiency are typically associated with smaller proportionate reductions in energy use. This shortfall is known as the rebound effect. Its primary cause is the fall in energy prices, as measured in efficiency units, which produce substitution and income effects. These tend to offset some of potential reductions in energy use generated through improvements in energy efficiency (Berkhout et al., 2000; Birol and Keppler, 2000; Brookes, 1990, 2000; Greening et al., 2000; Herring, 1999; Jevons, 1865; Saunders, 1992, 2000a,b; Schipper and Grubb, 2000; Van den Bergh, 2011). In order to fully identify rebound ideally a system-wide method should be adopted, with the most common approach being the use of multi-sector Computable General Equilibrium, CGE, models (Sorrell, 2007).

In this paper we investigate how the concept and treatment of economy-wide or 'macro-level' rebound can be extended to take into account these wider impacts that occur through international trade effects. Whilst Wei (2010) presents a theoretical analysis of 'global rebound' and there are a number of applied studies, including Barker et al. (2009), the potential spillover effects from energy efficiency improvements in one nation on energy use in other nations have generally been neglected (Madlener and Alcott, 2009; Sorrell, 2009; Turner, 2013; Van den Bergh, 2011). Our central aim is to test whether by ignoring changes in energy use in other countries we underestimate rebound effects.

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We therefore use a multi-region CGE world model, developed along the lines of the basic version of the WIOD CGE framework (Koesler and Pothen, 2013), to extend the spatial focus of the rebound literature.[1] The work involves simulating the impact on global energy use of increased energy efficiency in German industrial production. The specific aim is to identify the extent to which the measured rebound effects increase or fall when energy use outwith the country experiencing the initial efficiency improvement in included. This is an important knowledge gap, particularly given the global nature of energy-related climate change and the existence of supra-national policy targets, such as the EU 20-20-20 framework.

Section 2 derives the analytical expressions required to extend the rebound calculation to incorporate endogenous changes in energy use at extended spatial levels and considers the types of channel through which an efficiency improvement in energy used in production in one nation can spill-over to impact energy use in direct and indirect trade partners.[2] Section 3 provides an overview of the world CGE framework used and Section 4 outlines the simulation strategy. Sections 5 and 6 report results from two sets of simulations, both involving a 10% increase in energy efficiency in production in the German economy. In the Section 5, the energy efficiency improvement applies only to the Manufacturing sector. In Section 6, it applies to all production sectors. Figures are given for the change in key economic variables in Germany, the rest of the European Union (REU) and the rest of the world (ROW) and a number of rebound measures are calculated. Section 7 draws conclusions and recommendations for future research.

2. Extending the boundaries of the economy-wide rebound effect

In this paper we build on the economy-wide rebound specifications derived in Lecca et al. (2014). We consider the national and global general equilibrium rebound effect following an improvement in the efficiency with which energy is used first in one production sector and then across all production sectors in a single national economy.

2.1. Home economy effects

2.1.1. Energy efficiency improvements in a single sector

Own-sector rebound in the targeted sector i, (the sector receiving the efficiency improvement) is identified as R_i, and is reported in percentage terms. It implicitly incorporates general equilibrium feedback effects on sector i's energy use, in addition to direct and indirect rebound effects. It is defined as:

$$R_i = \left[1 + \frac{\dot{E}_i}{\gamma}\right]100, \tag{1}$$

where $\dot{E}_i$ is the change in energy use in sector i after all agents have adjusted their behaviour in consequence of the technical energy efficiency improvement,$\gamma>0$. Both the energy efficiency improvement,γ, and the change in energy use, $\dot{E}_i$, are given in percentage terms. If the percentage reduction in energy use equals the increase in productivity, so that $-\dot{E}_i = \gamma$, then R_i is zero and there is no own-sector rebound. However, if the proportionate reduction in energy use is less than the increase in efficiency, then rebound occurs.

The energy efficiency improvement impacts the own-sector energy use primarily through the following channels. First, there is substitution towards energy, measured in efficiency units, in production in the target sector. This reflects the fall in the price of energy used in that sector when that energy is measured in efficiency units. This means that the sector's proportionate fall in energy use per unit of output, now measured in natural units, is less than the efficiency improvement. The second channel is the increased competitiveness of the target sector. This is driven by the reduced costs associated with the fall in intermediate input use and generates increased demand for the output of the sector as product price falls. The increase in demand for the product is accompanied by an increase in the derived demand for the energy input. Both the substitution and competitiveness effects increase the rebound value.[3]

The first step in identifying the own-country economy-wide rebound effect is to consider the impact on total energy use in the aggregate production side of the economy (all $i = 1, \ldots,$ N sectors), E_p. The own-country total production rebound formulation, R_p, is given as:

$$R_p = \left[1 + \frac{\dot{E}_p}{\alpha\gamma}\right]100, \tag{2}$$

where α is the initial (base/reference year) share of sector i's energy use in total energy use in production (across all $i = 1, \ldots,$ N sectors) in the domestic economy. The term $\dot{E}_p/\alpha\gamma$ can be expressed as:

$$\frac{\dot{E}_p}{\alpha\gamma} = \frac{\Delta E_p}{\gamma E_i} = \frac{\Delta E_i + \Delta E_p^{-i}}{\gamma E_i} = \frac{\dot{E}_i}{\gamma} + \frac{\Delta E_p^{-i}}{\gamma E_i}, \tag{3}$$

where Δ represents absolute change and the $-i$ superscript indicates all production excluding sector i. Substituting Eq. (3) into Eq. (2) and using Eq. (1) gives:

$$R_p = R_i + \left[\frac{\Delta E_p^{-i}}{\gamma E_i}\right]100. \tag{4}$$

Eq. (4) indicates that the total (own-country) rebound in productive energy use depends on the net increase in aggregate energy use across all other domestic production sectors. As argued already, we expect the output of the target sector to rise and output in the energy sector to fall (as long as there is no 'backfire', i.e. rebound greater than 100%). An important third channel determining rebound is the reduction in energy use operating through the energy sector supply chain. Energy production is energy intensive. A reduction in demand for energy in the target sector will further reduce the demand for energy in the production of energy itself. This third channel reduces the rebound value. The intermediate energy demands across other sectors, that are not the target sector or the energy sectors, will reflect changes in the composition of final demand and the relative energy intensities of expanding and contracting sectors.

Using a similar procedure as outlined in Eqs. (3) and (4), and detailed in Appendix A, the full economy-wide rebound effect in the domestic economy, R_d, can be expressed as:

$$R_d = R_p + \left[\frac{\Delta E_c}{\gamma E_i}\right]100. \tag{5}$$

where the c subscript indicates 'consumption' (households). Eq. (5) implies that the total economy-wide rebound in the home country, R_d, will be larger (smaller) than rebound in the aggregate production sector, R_p, if there is a net increase (decrease) in energy use in household final consumption.

The changes in domestic energy used in household consumption in principle are driven by changes in product prices and household income. We expect real household income to rise as the result of the increase in energy efficiency, thereby increasing rebound. In the present

[1] This paper separately identifies all EU countries but treats the rest of the World (ROW) as a single aggregate entity. However, in the reported results the European Union is separated into Germany and the rest of the EU (REU) so that when we refer to regions, we mean aggregations of national states.

[2] Lecca et al. (2014) investigate the economy-wide impacts of increased efficiency in household energy use. These differ from the impacts generated by the improvements in productive energy use considered here.

[3] To reiterate, this is not direct rebound; rather it is the rebound calculated incorporating the change in energy use in sector i with all general equilibrium effects of the efficiency improvement taken into account.

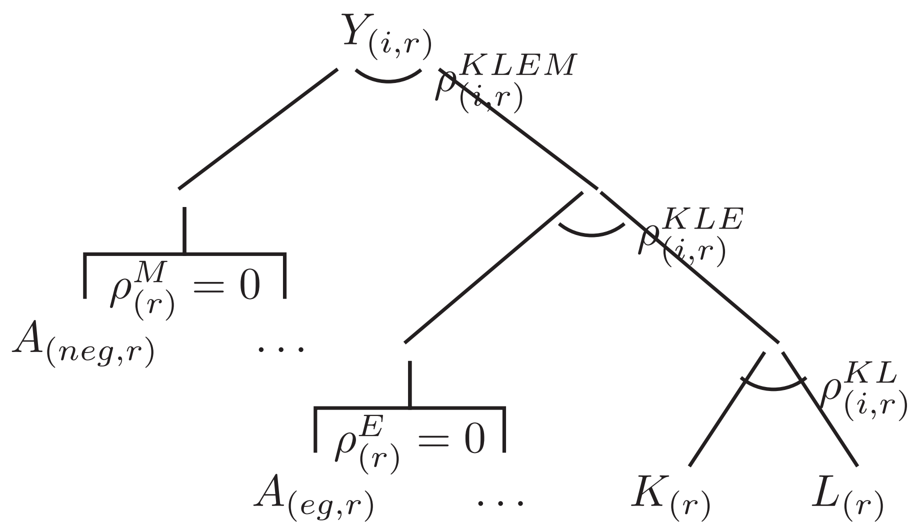

Fig. 1. Structure of commodity production.

model, in the default setting the composition of household consumption is held constant. This implies that measured rebound will rise with the incorporation of household consumption effects. However, we do perform simulations in which the composition of household consumption is sensitive to product price. Changes in price will depend on the general equilibrium adjustments to factor prices together with the change in the technology in the target sector. In so far as energy prices fall relative to other commodities, rebound will rise if price-sensitivity in household consumption is increased.

2.1.2. Energy efficiency improvements in all sectors

Where the energy efficiency gain applies to all sectors, there will be the same substitution effect leading to increased energy use in production, when measured in efficiency units. This now operates in all sectors and remains a major channel for rebound. On the other hand, the ultimate size of the competitiveness effect for individual sectors will be primarily driven by their energy intensity. However, with fixed, fully-employed, factors of production, which we assume here, output cannot rise in all sectors simultaneously. The price of factors in general will increase (although there will normally also be distributional effects). Therefore, some sectors will actually lose competitiveness, even though their energy efficiency has risen. Nevertheless, we expect that the more energy intensive sectors will experience the bigger cost reductions and therefore ultimately to be those that are more competitive after the efficiency increase. In this respect it is important to note that energy itself is a highly energy intensive sector, so that it is likely to be one of the sectors whose competitiveness increases the most.

2.2. Global economy effects

We are particularly interested in the international energy-use spillover effects. Therefore, we define a global rebound effect, R_g, relating to the total impact on energy use in all countries resulting from increased efficiency in the use of energy in sector i within the home economy, d. Again, adopting the approach detailed in Appendix A, this can be expressed as:

$$R_g = R_d + \left[\frac{\Delta E_g^{-d}}{\gamma E_i}\right]100 \qquad (6)$$

where E_g^{-d} represents global energy use outwith the domestic economy receiving the efficiency shock. Again, expression (6) shows that the total global rebound will be greater than the own-country economy-wide rebound if there is a net increase in external aggregate energy use following the efficiency improvement within country d. Note that it is possible to identify more than one region within the external global economy and disaggregate the changes in global non-domestic energy use accordingly. In the simulations reported in Sections 5 and 6 of efficiency improvements in German production, we separately identify the change in energy use in the rest of the EU-27 and the rest of the world.

In all cases the economies of countries that do not directly experience an improvement in energy efficiency are affected through three channels. Two of these relate to changes in trade-related demand (the changes in exports and import substitution). The third is the accompanying changes in intermediate and consumption demand.

The changes in trade-related demand are determined through competitiveness and composition of demand channels. The relative competitiveness effects are primarily governed by price changes in the home economy (i.e. the economy directly experiencing the efficiency improvement). If the price falls in a particular home sector, we expect that the competitiveness of the corresponding sector in other countries will fall with an accompanying negative impact on output. Similarly, if the composition of home-country import demand changes for non-price reasons, this affects the export demand in foreign countries. Such a demand change would include shifts in energy demand directly affected by the increased energy efficiency.

However, it is important to note that the changes in foreign energy exports or import substitution do not directly affect energy use in foreign countries. If more energy is exported this means that the energy is to be used elsewhere. However, the third, supply-chain, channel is important in this respect. This is the change in intermediate demands that accompanies the changes in trade-related demands.

There are additionally other general equilibrium impacts but these are likely to be less important. There are possible changes in the energy intensity of production that would accompany changes in relative energy prices. Similarly, if consumption demand increases through favourable changes in the terms of trade, this will affect energy demand. However, we expect the primary impact to come through changes in intermediate demand driven by changes in the size and composition of export demand.

3. The global CGE modelling framework

To evaluate the economy-wide rebound and provide a first analysis of the full global spill-over effects that accompany an increase in domestic energy efficiency, we use a static, multi-region, multi-sector CGE world model which has been developed along the lines of the Basic

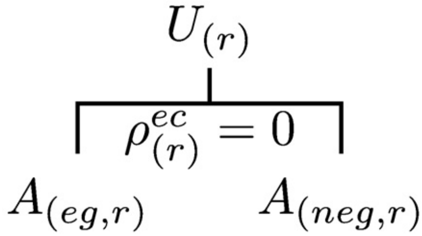

Fig. 2. Structure of utility function.

WIOD CGE (Koesler and Pothen, 2013). In the present analysis, the model features 28 separate regions. These comprise all the individual EU27 member states and Rest of the World (ROW). However, for ease of exposition, in presenting the simulation results we aggregate the outcomes for all EU member states apart from Germany, so that we report figures for Germany (GER), the Rest of the EU (REU) and the Rest of the World (ROW).

The model disaggregates production to eight sectors/commodities. Two are energy supply sectors/commodities: Electricity and gas, and coke, refined petroleum and nuclear fuel. The other six (non-energy supply) sectors/commodities are primary goods, food, drink and tobacco, manufacturing, construction, transport and services. The detailed mapping of these aggregate sectors to the original WIOD sectors is given in Table B.1 in Appendix B.

The production of each commodity is characterised by a KLEM production structure shown in Fig. 1, which features a CES function at every level and ρ represents the corresponding substitution parameter. Capital, $K_{(r)}$, and labour, $L_{(r)}$, enter the production function on the lowest level in the generation of value added. On the second level the value added composite is combined with the energy intermediate composite $A_{(eg,r)}$. This energy composite is a (fixed coefficients) Leontief aggregation comprising the commodities electricity and gas, and coke, refined petroleum and nuclear fuel. On the top level the energy-value-added composite is combined with a non-energy material aggregate $A_{(neg,r)}$ to create the sector gross output, $Y_{(i,r)}$.[4] The intermediate composite is also a Leontief aggregation of all six non-energy commodities identified above. Sectoral output can be used for intermediate use, final domestic consumption or exported. Commodities are made up of composites of the domestic production and imports, using the Armington (1969) assumption of incomplete substitution.

Each region has one aggregated representative agent who supplies a fixed amount of capital and labour. Both factors are immobile between regions but completely mobile across sectors within each region. All factors are fully employed, which determines the relevant wage and capital rental payments. This implies a Marshallian long-run interpretation of the simulation results, so that in each equilibrium all factor use is fully adjusted to the ruling factor and commodity prices.

The consumption decision of the representative agent embraces all the household and governmental (private and public) final demand in a region. The representative agent maximizes her utility by purchasing bundles of consumption goods subject to a budget constraint. The budget is determined by factor and tax income along with interregional borrowing or saving. The utility of representative agents $U_{(r)}$ is given as a Leontief composite of energy $A_{(eg,r)}$ and a non-energy commodities $A_{(neg,r)}$. The structure of the utility functions is shown in Fig. 2.[5]

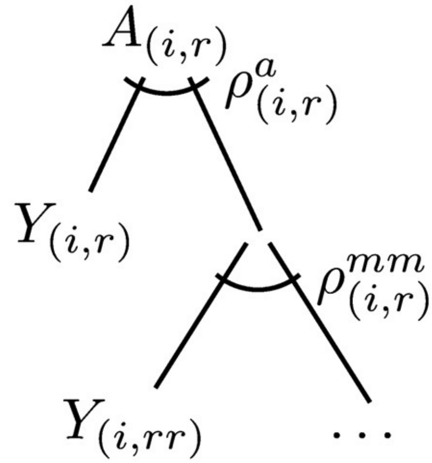

Fig. 3. Structure of Armington aggregate.

Regarding the basic economic structure, the model builds on data from the World Input–Output Database (WIOD) (Timmer et al., 2012; Dietzenbacher et al., 2013) and is calibrated to the year 2009.[6] The structure of the Armington trade aggregation is shown in Fig. 3, with the corresponding Armington elasticities taken from GTAP7 (Badri and Walmsley, 2008; Hertel et al., 2007, 2008). Koesler and Schymura (2015) provide substitution elasticities determining the flexibility of production with regard to inputs. These elasticities vary across sectors and regions. Maximum and minimum values are given Appendix B, Table B.4. A full account is given in Koesler and Schymura (2015).[7] Savings and borrowing are not directly reported in WIOD but they result from the imbalance of final demand and factor endowments or other sources of revenue (taxes, emission allowances, etc.). Overall macroeconomic balance is achieved by changes in interregional savings/borrowing, whilst the overall savings and borrowing of final demand agents are held constant. Prices are expressed against the numeraire which is taken to be the consumer price index (CPI) for the rest of the World.

4. Simulation strategy

We wish to simulate the impact of the adoption of energy-saving technological change in production. As is standard in rebound studies, we assume that this technological change is supplied as a public good. This implies that the efficiency improvement is taken to be costless in two respects. First, resources are not required to create the knowledge on which the efficiency improvement is based. Second, firms can implement the efficiency changes without using additional resources. We make these assumptions because rebound studies focus on the difference between actual and expected energy saving from the introduction of improved energy efficiency. It is the reduced cost of energy in efficiency units which drives the rebound effects. The simulations therefore attain maximum transparency if the efficiency improvements are assumed to be costless. In particular, it is important to distinguish the rebound effect, which is associated with pure efficiency improvements, from the wider impact of policies, such as carbon pricing or cap and

[4] There are other ways of structuring the nested KLEM production function and there are also other possible functional forms (Lecca et al., 2011). Alternative CES structures and functional forms will be investigated in future work.

[5] Modelling consumption on the basis of a Leontief function is restrictive, although it has recently been endorsed by Herrendorf et al. (2013). The adoption of fixed consumption coefficients implies that, inter alia, we do not account for rebound effects associated with changes in household consumption patterns arising from the assumed efficiency improvements in production. We thank an anonymous referee for pointing us to this limitation. We investigate the sensitivity of the rebound value to variations in the elasticity of substitution in consumption in Appendix B, Tables B.2 and B.3.

[6] The WIOD database is available at http://www.wiod.org. We use data downloaded on the 17th of April 2013.

[7] Koesler and Schymura (2015) fail to provide substitution elasticities between capital and labour for the "electricity and gas" sector or for the substitution elasticity between value-added and energy in the production of "coke, refined petroleum and nuclear fuel". For these sectors we assume an elasticity equal to the corresponding elasticity in the "manufacturing" (0.234) and the "chemical and chemical products" sectors (0.717) respectively.

trade schemes, which achieve a reduction in the use of energy only through the use of previously more costly techniques.[8]

We consider two scenarios. In both we apply a 10% increase in German energy efficiency in production.[9] In the first simulation this applies solely to the "Manufacturing" sector. In the second scenario, the energy efficiency stimulus is experienced by all eight German production sectors. In each case, the new post-shock equilibrium is then compared to the original equilibrium (without the efficiency changes) and the appropriate rebound values are calculated. This therefore represents a comparative static analysis in which all changes can be attributed to the efficiency shock.[10]

The energy efficiency shock is applied to the second nest of the treated sectors' production functions (see Fig. 2) which take the form:

$$CES^{KLEM}_{KLE(i,r)} = \left(\eta^{KLE}_{KL(i,r)}\left(CES^{KLE}_{KL(i,r)}\right)^{\rho^{KLE}_{(i,r)}} + \gamma^{Energy}_{(i,r)}\eta^{KLE}_{E(i,r)}\left(\min_{eg}\left(\frac{A_{(eg,r)}}{\eta^{E}_{(eg,r)}}\right)\right)^{\rho^{KLE}_{(i,r)}}\right)^{\frac{1}{\rho^{KLE}_{(i,r)}}}, \quad (7)$$

where, η are the input shares, ρ are the substitution parameters and γ^{Energy} indicates the level of energy efficiency which is normalised to be one in the initial equilibrium.[11] The proportionate change in demand for intermediate energy use would apply equally between domestic and imported electricity as long as relative electricity prices remained the same. In the first scenario the efficiency parameter, $\gamma^{Energy}_{i,GER}$, in Eq. (7), increases from its initial value of 1 to 1.1 in the German "manufacturing" sector only. In the second scenario, the parameter is increased across all German production sectors.

It is useful to give an indication of the size of shock that is to be given to the international economy through these efficiency changes. Table 1 shows the energy used in German Manufacturing and in German production as a whole as a share of total energy use in German production, the German economy as a whole, the combined EU and the world economy.[12] The data show that the energy use in Manufacturing makes up 28.6% of the total energy used in German production. Energy used in German production is 58% of total German domestic energy use, and 10.8% and 2.9% respectively of all EU and global energy use. It is clear that we would expect energy efficiency improvements in German Manufacturing and in German production as a whole to have impacts which would spread outwith the German national border.

5. Scenario 1: energy use impacts and rebound values for a 10% increase in energy efficiency in the German manufacturing sector

5.1. Domestic impacts

In this section we consider the effects of an energy efficiency improvement, targeted on the German Manufacturing sector. The relevant results are shown in Tables 2, 3 and 4, where German, rest of the EU (REU) and rest of the World (ROW) figures are given and all are reported as changes from the initial equilibrium. The rebound calculations are shown in Table 8.

The outcomes add numerical detail to the discussion in Section 2. We begin by considering the impact on the German economy. As expected, there is an increase in GDP (0.13%) which is reflected in the increase in a rise in the returns to capital and labour. However, these proportionate effects are small, driven by the limited scope of the efficiency

Table 1
The energy used in German manufacturing and German production expressed as a percentage of total energy used in German production, and the German, EU and World economies.

	German production (α)	German economy (β)	EU economy (φ)	World economy (χ)
German "manufacturing"	28.58	16.57	3.09	0.84
German production	100.00	57.99	10.81	2.95

Source: authors' calculations based on WIOD, (Timmer et al., 2012; Dietzenbacher et al., 2013).

Table 2
Change in key macroeconomic indicators. Scenario 1: 10% increase in energy efficiency in German manufacturing.

	Germany	REU	ROW
GDP (expenditure approach)	0.133%	−0.001%	0.000%
Exports	0.025%	−0.008%	−0.004%
Imports	0.032%	−0.007%	−0.005%
Public & private consumption	0.145%	0.000%	0.000%
CPI	0.231%	0.003%	0.000%
Capital rental	0.326%	0.009%	0.001%
Nominal wage	0.370%	0.008%	0.000%
Aggregate price of energy	0.244%	0.008%	0.000%
Consumption energy use	0.145%	0.000%	−0.000%
Industrial energy use	−1.497%	−0.007%	−0.003%
Total domestic energy use	−0.807%	−0.004%	−0.002%

Table 3
Changes in sectoral price, output and energy use. Scenario 1: 10% increase in energy efficiency in German manufacturing.

	Price	Output	Energy
Germany			
Electricity and gas	0.273%	−0.932%	−0.926%
Coke, refined petroleum and nuclear fuel	0.174%	−0.743%	−0.711%
Primary	0.263%	−0.674%	−0.691%
Food, drink and tobacco	0.248%	−0.552%	−0.591%
Manufacturing	−0.083%	0.433%	−4.356%
Construction	0.237%	0.115%	0.069%
Transport	0.282%	−0.277%	−0.181%
Services	0.319%	0.068%	0.061%
REU			
Electricity and gas	0.007%	0.007%	0.005%
Coke, refined petroleum and nuclear fuel	0.006%	−0.017%	−0.025%
Primary	0.006%	0.040%	0.040%
Food, drink and tobacco	0.006%	0.087%	0.084%
Manufacturing	0.000%	−0.072%	−0.078%
Construction	0.003%	0.003%	0.002%
Transport	0.006%	0.029%	0.030%
Services	0.004%	0.006%	0.004%
ROW			
Electricity and gas	0.000%	−0.001%	−0.001%
Coke, refined petroleum and nuclear fuel	0.000%	0.000%	−0.000%
Primary	0.000%	0.003%	0.003%
Food, drink and tobacco	0.001%	0.011%	0.012%
Manufacturing	0.000%	−0.018%	−0.019%
Construction	0.000%	0.000%	0.000%
Transport	0.001%	0.009%	0.009%
Services	0.000%	0.001%	0.002%

[8] However, the issue of the costs associated with efficiency improvements is one that is often raised in discussions of simulating efficiency changes. This is addressed in more depth in Appendix C.

[9] On average the energy efficiency of the German industry has increased by about 1.6% per annum (BMWi, 2013). In the process of our analysis, we also considered efficiency improvements of 5%, 20% and 30%. But the magnitude of the shock only affects the scale of the different effects and does not qualitatively change the underlying basic effects. Here we report findings which would correspond to just over 5 years worth of technical improvement, mapping to an energy efficiency improvement in production of 10%.

[10] In future work we aim to consider more sophisticated ways of simulating efficiency improvements, for example by modelling a link with R&D activity, as proposed by Fisher-Vanden and Ho (2010).

[11] There are differences in opinion concerning the way in which energy efficiency improvements in production should be introduced (Sorrell and Dimitropoulos, 2007). We adopt the present approach for computational reasons but plan to investigate other methods in future research.

[12] These proportions are also required for the calculation of the rebound values using Eqs. (2), (A3) and (A4) from Section 3 and Appendix A.

Table 4
Changes in output [billion 2009 USD]. Scenario 1: 10% increase in energy efficiency in German manufacturing.

	Germany	REU	ROW	World
Regional total	5.002	−0.860	−1.973	2.169
Electricity & gas	−1.579	0.054	−0.016	−1.541
Coke, refined petroleum and nuclear fuel	−0.526	−0.063	0.005	−0.584
Primary	−0.683	0.315	0.200	−0.168
Food, drink and tobacco	−0.940	0.824	0.424	0.308
Manufacturing	6.631	−3.124	−3.422	0.085
Construction	0.337	0.065	0.010	0.412
Transport	−0.424	0.245	0.255	0.076
Services	2.186	0.825	0.571	3.582

Table 5
Change in key macroeconomic indicators. Scenario 2: 10% increase in energy efficiency across all German sectors.

	Germany	REU	ROW
GDP (expenditure approach)	0.516%	−0.005%	−0.002%
Exports	−0.087%	−0.017%	−0.002%
Imports	−0.150%	−0.011%	−0.000%
Public & private consumption	0.495%	0.001%	−0.000%
CPI	0.208%	0.005%	0.000%
Price of capital	0.600%	−0.007%	−0.001%
Price of labour	0.717%	0.009%	0.000%
Price of energy (aggregate)	−1.2700%	−0.008%	−0.001%
Consumption energy use	0.495%	0.001%	−0.000%
Industrial energy use	−5.340%	−0.060%	−0.004%
Total domestic energy use	−2.889%	−0.039%	−0.003%

improvement: the increase in the real wage, calculated as the percentage change in the nominal wage minus the percentage change in the consumer price index (CPI), is 0.14%, whilst the increase in the real payment to capital, calculated in a similar way, is less at 0.09%. Total consumption rises, broadly in line with GDP and incomes, and both aggregate exports and imports also increase. Energy use in public and private consumption increases at the same rate as total consumption; that is by 0.15%, which reflects the fixed coefficients assumed in the consumption function.[13] However, the industrial use of energy falls by 1.50% driven primarily by the fall in energy use in Manufacturing. As a result, total domestic energy use declines by 0.81%.

To get a greater understanding of the factors underpinning these results, it is useful to turn to Tables 3 and 4 which give sectorally disaggregated information. Again we focus initially on the figures for the German economy. The impact on prices is very clear: Manufacturing prices fall by 0.08%, reflecting the direct improvement in technical efficiency, whilst the prices in all other sectors rise within the range 0.17% and 0.32%, broadly in line with the increases in nominal wages and capital rentals.[14]

The accompanying impact on sectoral outputs is similarly clear cut. Table 4 shows a relatively large increase in output in Manufacturing of \$6.6 billion (0.43%). This is stimulated by a rise in exports, substitution in favour of domestic Manufacturing goods over imports and increased domestic income as German Manufacturing goods become relatively cheap. There are also increases in output in other sectors that mainly supply the domestic (public and private) consumption, with an expansion in the service and construction sectors. Output falls in the energy sectors (Electricity and Gas, and Coke, Refined Petroleum and Nuclear Fuel) primarily as a result of the direct improvements in energy efficiency in manufacturing. Finally, there are also falls in other sectors more dependent on foreign trade, such as the Food, Drink and Tobacco, Transport and Primary sectors, which experience reduced competitiveness. Overall, imports rise as the German economy expands and non-manufacturing sectors lose competitive. In total, output increases by \$5.0 billion.

The figures in column 3 of Table 3 give the sectorally disaggregated proportionate changes in energy use indicating that the reduction in German Manufacturing is 4.36%. Using Eq. (1), this translates to an own-sector rebound value, R_i, of 56.4%, shown in the first line in Table 8.[15] The primary interest of this paper is to investigate how rebound values change as the scope of the measure is extended from own sector energy use to incorporate energy use in other sectors, other (consumption) uses and other economies. It is sometimes implied that such increases in scope will necessarily increase the rebound value. Our results show that this is not the case.

The first extension is to include the use of energy in production in the other German sectors, so as to calculate the own-country production rebound value, R_p, using Eq. (2). Table 3 reports a reduction in energy use in all sectors apart from small proportionate increases in Construction and Services and Table 2 shows a reduction in total German industrial energy use of 1.50%. This figure, together with the value of α, the share of manufacturing in total energy use in German production, from Table 1, is used to calculate the rebound value of 47.63%. This reduction in rebound occurs primarily because of the fall the output in the energy sectors, which are themselves energy intensive. The price of energy falls relative to the components of value added but increases in price relative to other commodities, so that the change in the energy intensity of production within individual sectors will be small.

A similar procedure, given by Eq (5) and outlined in Appendix A, is used to calculate the total domestic rebound value, $R_{d.}$, in the target economy (Germany). This measure incorporates energy used in domestic private and public consumption. In this case, the rise in GDP drives increases in private and public consumption increases, generating a rise in energy use in consumption by an equal proportionate amount. This leads to a rise in the rebound value to 51.3%.

5.2. Global effects

As indicated earlier, we are primarily concerned with the impacts of an increase in efficiency in production in Germany on energy use outwith the nation's boundaries. It is instructive to begin by considering Table 4. The efficiency improvement in Germany increases world output by \$2.2 billion. German output increases by \$5.0 billion, but there are reductions in the aggregate value of output in REU and ROW of \$0.9 and \$2.0 billion respectively. The German sector most strongly affected by the efficiency improvement is Manufacturing, and the increase in its competitiveness has an important direct impact on the REU and ROW economies. In particular, Table 4 indicates that the \$6.6 billion expansion in output in German Manufacturing essentially simply displaces Manufacturing output in REU and ROW, which fall by \$3.1 billion and \$3.4 billion respectively.

The shift of resources out of Manufacturing means that in REU and ROW economies the output in almost all other sectors increases. In both countries the biggest absolute increase in output is in Services. However, there are also large increases in Food, Drink and Tobacco, Transport and in the Primary sectors, which experience a decline in output in Germany. Clearly crowding out in these sectors in Germany leads to expansion in the rest of these external economies.

From the results reported in Table 2, it is clear that the total domestic energy use in both REU and ROW falls as a result of the energy efficiency gain in German Manufacturing. In both regions, total output declines and there is a large reduction in Manufacturing output. The result is that the rebound incorporating all changes in energy use in the EU, EUR_g, takes a value of 50.22%, that is slightly less than the German whole-economy domestic rebound. Similarly the world rebound value, $WorldR_g$, is lower still at 48.11%.

[13] This is subject to sensitivity analysis in Appendix Tables B2 and B3.

[14] Recall that the numeraire is the CPI in the rest of the world. The reported price changes are therefore relative to a basket of ROW prices.

[15] Recall that this is not limited to direct rebound in that it incorporates all the general equilibrium effects that impact on this sector.

Table 6
Changes in sectoral price, output and energy use. Scenario 2: 10% increase in energy efficiency across all German sectors.

	Price	Output	Energy
Germany			
Electricity and gas	−1.424%	−1.966%	−6.840%
Coke, refined petroleum and nuclear fuel	−0.906%	−0.598%	−5.036%
Primary	−0.241%	0.781%	−4.748%
Food, drink and tobacco	−0.094%	0.528%	−6.559%
Manufacturing	0.017%	0.020%	−4.075%
Construction	0.211%	0.415%	−7.274%
Transport	−0.378%	0.655%	−2.963%
Services	0.391%	0.298%	−5.992%
REU			
Electricity and gas	−0.005%	−0.186%	−0.199%
Coke, refined petroleum and nuclear fuel	−0.004%	−0.365%	−0.382%
Primary	0.002%	−0.086%	−0.077%
Food, drink and tobacco	0.002%	−0.014%	−0.011%
Manufacturing	0.005%	0.028%	0.052%
Construction	0.006%	0.002%	0.008%
Transport	0.006%	−0.051%	−0.037%
Services	0.006%	0.010%	0.020%
ROW			
Electricity and gas	−0.001%	−0.035%	−0.034%
Coke, refined petroleum and nuclear fuel	−0.001%	−0.038%	−0.037%
Primary	0.000%	−0.022%	−0.020%
Food, drink and tobacco	0.000%	−0.003%	−0.002%
Manufacturing	0.001%	0.012%	0.017%
Construction	0.000%	0.000%	0.001%
Transport	0.000%	−0.016%	−0.015%
Services	0.000%	0.003%	0.005%

6. Scenario 2: energy use impacts and rebound values for a 10% increase in energy efficiency in all German production

6.1. Domestic impacts

In this simulation we introduce an across the board 10% improvement in energy efficiency in production in all German sectors. The effects on key aggregate and sectorally disaggregated economic variables are reported in Tables 5, 6 and 7. The first key point from Table 5 is that, as we would expect, the size of the response to the supply-side shock to the German economy is much larger than in Simulation 1. German GDP increases by 0.52%, the increase in the real returns to labour and capital are 0.51% and 0.39% respectively and private and public consumption increases by 0.49%. However, the proportionate changes in REU and ROW variables are still low, and this is especially important for prices, where the change are small relative to the those that occur in Germany. Recall that the ROW CPI is taken as the numeraire and therefore remains unchanged and the increase in the REU CPI is 0.003% as against the increase in Germany of 0.23%.

The resulting variation in German commodity prices at a sectoral level primarily reflects the energy intensity of the commodity but, as secondary effects, also the sector's labour, capital and import intensities.

Table 7
Changes in output [billion 2009 USD]. Scenario 2: 10% increase in energy efficiency across all German sectors.

	Germany	REU	ROW	World
Regional total	10.117	−1.311	−0.065	8.741
Electricity & gas	−3.331	−1.364	−0.713	−5.408
Coke, refined petroleum and nuclear fuel	−0.423	−1.326	−0.648	−2.397
Primary	0.791	−0.672	−1.587	1.468
Food, drink and tobacco	0.900	−0.134	−0.099	0.667
Manufacturing	0.305	1.210	2.286	3.801
Construction	1.222	0.035	0.006	1.263
Transport	1.006	−0.424	−0.469	0.113
Services	9.647	1.364	1.158	12.169

Table 8
General equilibrium rebound effects for scenarios 1 (10% increase in energy efficiency in German manufacturing) and scenario 2 (10% increase in energy efficiency across all German sectors).

	Own-sector R_i	Own-country production R_p	Own-country total R_d	Global	
				EUR_g	$WorldR_g$
Scenario1					
Rebound [%]	56.44	47.63	51.31	50.22	48.11
Change [percentage points]		−8.81	3.68	−1.09	−2.11
Scenario 2					
Rebound [%]	n.a	46.60	50.18	47.28	46.58
Change [percentage points]			3.58	−2.09	−0.70

The figures in Table 6 show the biggest reductions in price occurring in the energy sectors themselves, Electricity and Gas, and Coke, Refined Petroleum and Nuclear Fuel, reflecting their high energy intensity in production.[16] Other sectors where prices fall are Transport, Primary and Food, Drink and Tobacco. Note that in the labour intensive Services, Construction and Manufacturing sectors, prices rise.

Output falls in the two energy sectors but increases in all others. The proportionate figures reported in Table 6 are slightly misleading: from Table 7 we observe that the sector that has the second smallest (0.2978%) proportionate increase in output, Services, has the largest ($9.6 billion) absolute increase. The 0.49% rise in domestic consumption demand is driving this change in Services output and the increase in the output in this sector requires resources to be shifted from other sectors. We know that the energy sectors will release resources and the relatively small increase in output in Manufacturing implies that resources will be released here too. In this simulation, overall both German exports and imports fall, so that the increase in activity involves import substitution. Domestic private and public consumption of energy increases by 0.49% but this is completely dominated by the 5.34% fall in industrial energy use, so that total domestic energy use declines by 2.89%.

The domestic rebound values where the energy efficiency improvement applies across all German sectors, are very similar to those where the efficiency improvement is only in Manufacturing. The Scenario 2 value is slightly less than that for Scenario 1 but the qualitative relationship between the different rebound measures is retained. There is a substantial rebound of 46.60% in energy use in total German production. When the whole economy rebound is calculated, the value is increased by 3.58 percentage points as a result of the increase in energy use in public and private consumption.

6.2. Global impacts

The sectoral responses from both the REU and ROW economies are, in this case, qualitatively similar. Total output summed across all sectors falls in both regions: by $1.311 billion in the REU and by $0.065 billion in ROW. There are reductions in output in the two energy sectors, reflecting both the lower industrial demand in Germany plus the increased competitiveness of the German energy sectors. These output reductions in the REU and ROW energy sectors are less, in absolute terms, than the corresponding declines in Germany. However, they make up almost 40% of the world reduction in the energy output resulting from the improvement in German energy efficiency. Also these energy sectors are the sectors generally showing the largest absolute reductions

[16] Changes in demand for a commodity only affect its price in this long-run model in so far as they change the economy wide factor prices. As a result of the general equilibrium adjustments after a shock, it is quite possible for the demand for a commodity to rise, with no change in its technology, but for its price to fall.

in output in REU and ROW. Only the Primary sector in the ROW registers a bigger fall.

In the Services, Construction and Manufacturing sectors, REU and ROW output increases in line with the expansions in the German economy. In Germany these are sectors that benefited from the German expansion in consumption, but have become less competitive against production in REU and ROW. On the other hand, the Food, Drink and Tobacco and Primary sectors show reductions in REU and ROW outputs which are moving contrary to the changes in German output. These are REU and ROW sectors which are now less competitive than their German counterparts.

The proportionate impact on aggregate variables in REU and ROW is shown in Table 5. In REU, private and public consumption of energy increases but this is dominated by the reduction in production, so that total domestic energy use falls by −0.04%. In ROW, energy use in both private and public consumption and in industry falls, with total ROW domestic energy use declining by −0.003%. Again, as was observed in the rebound associated with the Scenario 1 simulations, the extension to include REU and ROW energy use reduces the measured rebound. The combined effect in this case is a slightly larger reduction of 3.60 percentage points with the biggest reduction occurring in the REU segment.

7. Conclusions and directions for future research

In the case of policies to increase energy efficiency, a major concern has been the existence of rebound effects. These effects operate through the reduction in the price of energy in efficiency units, which thereby generate substitution and income effects which operate to at least partly offset the reduction in energy use generated by the direct efficiency gain. This paper extends the analyses of 'economy-wide' rebound from the national focus of previous studies. In particular it investigates whether international spill-over effects from trade in goods and services have the potential to change the overall (global) rebound of local energy efficiency improvements. On that account, we propose a measure of economy-wide rebound that is appropriate for use if the accounting boundaries are expanded beyond the borders of the national economy where the efficiency improvement takes place. Whether rebound rises or falls as the boundaries are extended depends on whether there is a net increase or decrease in energy use in the area of activity being introduced.

Our model suggests that at the global scale rebound effects are significant. 10% energy efficiency improvements in German Manufacturing and in German production overall are associated with global rebound values of 48.11% and 46.58%. That is to say, almost a half of any expected energy saving through improved energy efficiency in production will be taken by rebound effects. However, the results do not show that restricting the focus of the rebound calculation to the economy in which the improvement occurs underestimates the rebound effect: quite the reverse. The rebound values fall in both of the simulation scenarios performed here where the energy use outwith Germany is incorporated in the rebound calculation.

The logic is straightforward. The standard energy leakage argument concerns policies where firms are encouraged to reduce energy consumption by making energy relatively expensive (through a carbon-tax, regulation or cap and trade policy). However, the rebound phenomenon occurs around policies which encourage the adoption of energy saving technologies where, in the treated activities, energy efficiency improves. Especially where the policy extends across all production sectors, the relative competitiveness of energy intensive commodities in target country increases. This means that in other countries their production will, in general, become less profitable, and therefore be discouraged. This is reflected in the results obtained in this paper. In the simulations we report, the value of the domestic rebound actually overestimates the global rebound. Of course, we use a general equilibrium system, so that other forces are simultaneously at work. Further, the size and detail of the rebound effects will differ in specific cases.

For pedagogic reasons, the model we use here imposes a number of limiting assumptions. Key amongst these are: that that there is no substitution across commodities in consumption; that supplies of capital and labour are fixed in each country; and that all factors of production are always fully employed.

Sensitivity analysis, reported in Tables B2 and B3 in Appendix B suggest that increasing the elasticity of substitution between commodities in consumption will increase domestic and global rebound values. However, the qualitative character of the results remains. The rebound values measures that incorporate changes in energy use outwith Germany have lower values and the size of the difference remains relatively stable. Nonetheless, relaxing the Leontief assumption in the household utility function is a priority for future research in order to improve consideration of how production-side efficiency gains affect household-side consumption patterns and, in turn, affect economy-wide energy consumption and rebound.

In future developments, another key priority must be to relax assumptions on the supply-side of the interregional global CGE modelling framework. First, a key area will be the introduction of a more flexible and sophisticated treatment of capital and labour markets. This would involve consideration of investment, labour supply and migration. Moreover, modelling capital stock and labour market adjustments across regions would introduce dynamic adjustment of factor supply which would allow investigation of the evolution of global rebound over time.

Second, given its importance in our results, a priority must be to develop a more sophisticated treatment of energy supply. This should include (but not be limited to) consideration of the manner in which capacity decision are actually made (which adds emphasis to the need to effectively model dynamic adjustment in general), the impact of increasing exploitation of renewable energy sources and technologies, and how energy prices are determined in local and international markets.

Another area that should be the focus of future research is to consider how the nested production function used in the CGE model may be reformulated to better match the energy-augmenting technical progress paradigm. This issue is a more general one for the introduction of energy efficiency improvements, not limited to CGE analyses, with Sorrell and Dimitropoulos (2007) providing a detailed examination of this particular controversy.

Finally, applications of the type of modelling framework presented in this paper (and further augmented in ways already discussed) would be invaluable in considering the domestic and international spill-over effects of domestic policies designed to increase efficiency in household energy use, and the implications in terms of interdependence between energy efficiency policy implementation (for example, under EU 20-20-20) in one nation and energy use in others.

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Appendices A–C. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2015.12.011.

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