

## Supplementary Information

### S1 - CGE studies of rebound effects following energy efficiency improvements by producers

Study	Type, Region and no. of production sectors <sup>1</sup>	Nesting structure in production and key substitution elasticities <sup>1</sup>	Modelled energy efficiency improvement(s)	Rebound metric  System boundary	Baseline estimate of rebound effect and <u>Range of estimates in sensitivity tests</u>	Effect of specific sensitivity tests on estimated rebound effect	Comments
Vikström [1]	Dynamic  Sweden  Sectors=25	KE,L  Elasticities vary by sector $\sigma_{K,E} = 0.12$ to $0.87$ $\sigma_{KE,L} = 0.17$ to $0.87$	15% (12%) in non-energy (energy) sectors.	Energy  Regional	Baseline: <b>60%</b>	No	Applies to 1957-1962 period in which estimated changes in energy efficiency, factor inputs and total factor productivity are combined in turn. Results apply only to energy efficiency component, with fixed labour supply.
Grepperud, et al. [2]	Dynamic  Norway  Sectors=49	Not specified  Elasticities vary by sector: $\sigma_{K,E} = 0$ to $1$ $\sigma_{KE,L} = 0$ to $1$	Doubling growth rate of electricity productivity in paper, metals, chemicals & finance (in turn), and growth rate of oil productivity in fisheries and road transport (in turn)	Energy  Regional	Baseline: Rebound effects not quantified but appear relatively modest in fisheries and road transport, larger in paper and chemicals, and >100% in metals	No	Baseline scenario to 2050, reflecting government projections of economic growth, labour force growth, technological progress, carbon pricing etc. Efficiency scenarios increase the productivity of energy within six sectors in turn. Rebound effect is higher in sectors where there is greater scope for substitution between energy and other inputs. However, rebound exceeds 100% in metals sector, despite low substitution possibilities, owing to large output effect. Wide variation in results between sectors demonstrates how impacts can be complex, counterintuitive and context specific.
Allan, et al. [3]	Dynamic  UK  Sectors=25	KL,EM  All sectors: $\sigma_{E,M} = 0.3$ $\sigma_{KL,EM} = 0.3$ .	5% in all production sectors	Energy  Regional	Baseline (long-run): Elec= <b>27%</b> , Non Elec= <b>31%</b>  Range in sensitivity tests: Elec= <b>12 to 58%</b> Non Elec= <b>13 to 67%</b>	a) $\sigma_{E,M}$ : i) 0.1; ii) 0.7 Elec=i) <b>12%</b> ; ii) <b>58%</b> NonElec i) <b>13%</b> ; ii) <b>67%</b>  b) $\sigma_{KL,EM}$ : i) 0.1; ii) 0.7 Elec=i) <b>14%</b> ; ii) <b>53%</b> NonElec i) <b>22%</b> ; ii) <b>49%</b>  c) export demand elasticities i) 2.0; ii) 5.0 Elec=i) <b>28%</b> ; ii) <b>28%</b> NonElec i) <b>30%</b> ; ii) <b>32%</b>  d) recycling tax revenues	Multi-period simulation with capital investment a function of the difference between desired and actual capital stock. Simulates efficiency improvements in all production sectors, including energy sectors. The latter lead to a large rebound through both productivity improvements and lower energy prices. Demand for energy is inelastic, so the increase in quantity demanded is less than proportionate to the drop in price - leading to a decline in revenue, profitability and the return on capital in the energy sector and triggering a contraction in capacity over the long-term (disinvestment). This explains why the estimated long-run rebound effects are smaller than the short-run effects. Sensitivity tests demonstrate that the estimates are highly sensitive to the assumed elasticity of substitution between energy

Study	Type, Region and no. of production sectors <sup>1</sup>	Nesting structure in production and key substitution elasticities <sup>1</sup>	Modelled energy efficiency improvement(s)	Rebound metric  System boundary	Baseline estimate of rebound effect and Range of estimates in sensitivity tests	Effect of specific sensitivity tests on estimated rebound effect	Comments
						i) expenditure ↑ ii) income tax ↓ Elec=i) <b>26%</b> ; ii) <b>33%</b> NonElec i) <b>31%</b> ; ii) <b>40%</b>  d) labour supply elasticity i) zero ii) infinite Elec=i) <b>21%</b> ; ii) <b>47%</b> NonElec i) <b>24%</b> ; ii) <b>55%</b>	and materials, and between value-added and intermediates (easier substitution leads to larger rebound). A more elastic labour supply also leads to a larger rebound. Changes in both export demand elasticities and the treatment of tax revenues have a smaller effect.
Hanley, et al. [4]	Dynamic  Scotland  Sectors=25	KL,EM  Elasticities for all sectors: $\sigma_{E,M} : 0.3$ $\sigma_{KL,EM} : 0.3$	5% in all production sectors	Energy  Regional	Baseline (long-run) Elec= <b>131%</b> , Non Elec= <b>134%</b>  Range in sensitivity tests: Elec= <b>41 to 250%</b> Non Elec= <b>35 to 244%</b>	a) $\sigma_{E,M} : i) 0.1; ii) 0.7$ Elec=i) <b>113%</b> ; ii) <b>169%</b> NonElec i) <b>114%</b> ; ii) <b>174%</b>  b) $\sigma_{KL,EM} : i) 0.1; ii) 0.7$ Elec=i) <b>128%</b> ; ii) <b>139%</b> NonElec i) <b>129%</b> ; ii) <b>144%</b>  c) ROW export demand elasticities i) 2.0; ii) 5.0 Elec=i) <b>132%</b> ; ii) <b>135%</b> NonElec i) <b>134%</b> ; ii) <b>140%</b>  d) RUK export demand elasticities i) 2.0; ii) 5.0 Elec=i) <b>82%</b> ; ii) <b>136%</b> NonElec i) <b>67%</b> ; ii) <b>142%</b>  e) labour market closure Elec= <b>124%</b> NonElec <b>125%</b>  f) efficiency improvement in energy sectors only Elec= <b>250%</b>	Similar approach to Allan, et al. [3], but for Scotland. Very high rebound estimates largely driven by the electricity sector - efficiency improvements improve competitiveness, lower electricity prices and increase electricity exports rest of the UK (RUK). This displaces RUK electricity generation, so the net impacts in the UK should be smaller. But while these effects are sensitive to the elasticity of export demand to RUK, reducing this elasticity from 5.0 to 2.0 still leads to rebound effects of 82% (Elec) and 67% (Non Elec). In contrast, the rebound estimates are insensitive to the elasticity of export demand to the rest of the world (ROW). The estimated rebound effects are much smaller (Elec=41%, NonElec= 35%) when the modelled efficiency improvements are confined to non-energy sectors. Sensitivity tests demonstrate that easier substitution leads to larger rebound, with the elasticity between electricity and materials having a larger influence than that between value-added and intermediates. In contrast, changing the labour market closure (wages are determined at the UK level rather than Scottish level) has a much smaller impact.

Study	Type, Region and no. of production sectors <sup>1</sup>	Nesting structure in production and key substitution elasticities <sup>1</sup>	Modelled energy efficiency improvement(s)	Rebound metric  System boundary	Baseline estimate of rebound effect and Range of estimates in sensitivity tests	Effect of specific sensitivity tests on estimated rebound effect	Comments
						NonElec <b>244%</b>  g) efficiency improvement in non-energy sectors only Elec= <b>41%</b> NonElec <b>35%</b>	
Anson, et al. [5]	Dynamic  UK  Sectors=25	KL,EM  Elasticities for all sectors: $\sigma_{E,M} = 0.3$ $\sigma_{KL,EM} = 0.3$ .	5% in commercial transport sector	Energy  Regional	Baseline (long-run) <b>39%</b>  (Short run = 36%)  Range <b>37% to 105%</b> in sensitivity tests	Lon-run impacts:  a) 1% and 10% improvements = <b>37% and 41%</b>  b) Transport export demand elasticity from 2.0 to 4.0 = <b>44%</b>  c) $\sigma_{KL,EM}$ in transport=1.0 = <b>41%</b>  d) $\sigma_{E,M}$ in transport: 1.0 = <b>105%</b>	Similar approach to Allan, et al. [3], but focusing solely upon efficiency improvements in commercial transport. Long-run rebound is larger than short-run, but 'disinvestment effects' in the energy supply sectors (particularly Scottish oil) reduce its size. Sensitivity tests are confined to the parameters for the commercial transport sector and suggest that rebound is relatively insensitive to the scope for substitution between value-added and intermediates, but highly sensitive to the scope for substitution between energy and materials. Increasing the latter from 0.3 to 1.0 within the transport sector alone almost triples the estimated rebound effect, leading to backfire. The results also suggest that larger efficiency improvements lead to larger rebound.
Guerra, et al. [6]	Static  Spain  Sectors=16	(KL,E),M  Elasticities for all sectors: $\sigma_{K,L} = 0.3$ $\sigma_{KL,E} =$ not specified $\sigma$ =between energy types = 0	5% in all production sectors	Energy and Carbon  Regional	Baseline: Energy = <b>87%</b> Carbon = <b>123%</b>  Energy range <b>15 to 230%</b> in sensitivity tests  Carbon range <b>70 to 234%</b> in sensitivity tests	a) $\sigma_{KL,E} = 0$ Energy = <b>15%</b> Carbon = <b>70%</b>  b) $\sigma_{KL,E} = 1.0$ Energy = <b>177%</b> Carbon = <b>172%</b>  b) $\sigma_{KL,E} = 1.5$ Energy = <b>230%</b> Carbon = <b>235%</b>	Guerra and Sancho estimate a very large rebound effect for energy, and backfire for carbon emissions, following an efficiency improvement in all Spanish production sectors (including energy sectors). These estimates are highly sensitive to the assumed elasticity of substitution between value-added and energy, with easier substitution leading to larger rebound. Guerra and Sancho argue that earlier CGE studies underestimate the economy-wide rebound effect because they neglect the energy savings along the supply chain when estimating the <i>potential</i> energy savings from the efficiency improvement. For example, they neglect the energy saved in extracting and processing oil when estimating the potential energy savings from improving vehicle fuel efficiency. Guerra and Sancho estimate these savings with an input-output model, but find they make a relatively small difference to the estimated rebound effect. For example, including

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							the supply-chain energy savings in Guerra and Sancho's baseline scenario increases the estimated rebound effect from 87% to 91%. Most subsequent studies have continued to ignore these supply-chain savings when estimating the potential energy savings from the efficiency improvement [7].
Broberg, et al. [8]	Dynamic  Sweden  Sectors=27	KL,EM  Elasticities vary by sector $\sigma_{KL,EM}$ = mean 0.34 (range 0.1 to 0.7) $\sigma_{E,M}$ = mean 0.46 (range 0.1 to 0.9)  Higher (0.7 to 0.9) in energy-intensive sectors	5% in: 1) all sectors; 2) non-energy sectors; 3) energy-intensive sectors	Energy  Regional	Baseline:  1) All sectors = <b>73%</b>  2) Non-energy sectors = <b>69%</b>  3) Energy-intensive sectors = <b>78%</b>  Range <b>41 to 81%</b> in sensitivity tests	With efficiency improvement in non-energy sectors (baseline 69%):  a) 50% reduction in $\sigma_{E,M}$ in i) all sectors, ii) energy-intensive sectors = i) <b>41%</b> , ii) <b>60%</b>  b) flexible labour supply = <b>81%</b>  c) costly energy efficiency = <b>52%</b>	Similar approach to Allan, et al. [3], but for Sweden. In contrast to Allan, et al. [3], the energy sectors are not critical to the size of the rebound effect, partly because Sweden is not a fossil fuel producer and the scope to expand electricity exports is constrained by transmission capacity. The large estimate of rebound effects is driven instead by the dominance of energy-intensive industry - efficiency improvements in these sectors trigger a large increase in economic activity. Confining the efficiency improvement to these sectors leads to the largest estimate of the rebound effect. Households are indirectly affected by these efficiency improvements (their income and hence energy use increases) but this makes only a small contribution to the total rebound. Sensitivity tests demonstrate that the estimated rebound is highly sensitive to the assumed elasticity of substitution between energy and materials - with the scope for substitution in energy-intensive sectors being particularly important. With a more flexible labour supply (e.g. with migration), there is no increase in the real wage, which leads to higher GDP, higher consumption, higher exports, higher energy use and larger rebound – although the impact on the latter is relatively modest. The 'costly energy efficiency' scenario holds production costs constant by reducing the productivity of value-added. This eliminates output and income effects, but substitution effects still lead to a large rebound (an interesting result, since this is one of the few studies to include investment costs).
Yu, et al. [9]	Static  Georgia (US)	KL,EM	10% in:	Energy  Regional	Baseline:  Elec= <b>12%</b>	a) $\sigma_{KL,EM}$ : 0.3 and 0.7= <b>10% and 13%</b> (Elec),	Rare study of a small regional economy with a high level of sectoral disaggregation. Gives lower estimates of the rebound effect than most studies, but the reasons for

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	Sectors=69	Elasticities in central scenario: $\sigma_{KL,EM} = 0.5$ $\sigma_{E,M} = 0.3$ $\sigma_{Elec,NElec} = 1$	a) all sectors; b) each sector individually		NonElec= <b>25%</b> (coal=10%, gas=14%, oil=31%)  Range in sensitivity tests: Elec= <b>10 to 13%</b> NonElec= <b>22 to 27%</b>  Range of estimates by sector: <b>-18 to 73%</b> (NonElec) <b>-309% to 728%</b> (Elec)	<b>22% and 27%</b> (NonElec)	this are unclear. Energy market effects are relatively modest, since initial price decrease is offset by the increased demand from output effects and factor substitution. Remarkably wide range of estimates for individual sectors (especially for electricity), reflecting variations in energy intensity, scope for substitution, output elasticity and linkages with other sectors. Rebound effects are higher in energy and transport sectors, in sectors that are directly upstream or downstream of energy producers, and in sectors with a high output elasticity.
Garau, et al. [10]	Static  Italy  Sectors=21	KL,E  Elasticities in all sectors: $\sigma_{KL,E} = 0.24$ $\sigma_{K,L} = 0.52$	1% in all production sectors	Energy  Regional	Baseline: Long-run (short-run): Total= <b>21%</b> (26%) Coal=2% (-40%) Oil=15% (-19%) Gas=27% (40%) Elec=61% (59%)  Range <b>5% to 210%</b> in sensitivity tests (long-run)	a) KE,L nesting $\sigma_{KE,L} = 0.92$ , $\sigma_{K,E} = 0.98$ Long-run, total= <b>120%</b>  b) LE,K nesting $\sigma_{LE,K} = 0.46$ , $\sigma_{L,E} = 0.80$ Long-run, total= <b>100%</b>  c) All nesting structures: i) $\sigma_{i,j} = 0.01$ ; ii) $\sigma_{i,j} = 0.5$ ; iii) $\sigma_{i,j} = 0.9$ ; and iv) $\sigma_{i,j} = 1.5$  Long-run total: <b>i) 5%; ii) 63%;</b> <b>iii) 121%; iv) 210%</b>	Uses substitution elasticities from Van der Werf [11] who estimates CES production functions directly for Italy. The baseline KL,E structure gives relatively modest rebound effects, but the alternative nesting structures (again using substitution elasticities from Van der Werf [11]), lead to backfire. However, the results suggest that substitution elasticities matter more than nesting structure, since the estimated rebound effects are similar for each nesting structure when the substitution elasticities are identical. Easier substitution leads to larger rebound, with backfire for $\sigma_{i,j} \geq 0.9$ . Model results also show that long-run rebound is larger than short run rebound for some energy carriers (e.g. electricity) but lower for others (e.g. gas). Again, disinvestment effects play a role.
Lu, et al. [12]	Static  China  Sectors=135	KL,E,M (Leontief)  Elasticities in all sectors: $\sigma_{K,L} = 0.5$ $\sigma_{KL,E} = 0.0$ (Leontief)  $\sigma$ =between energy types = 0.5 in non-	5% for each energy type in turn	Energy  Regional	Baseline:  Long-run (short-run): Coal= <b>21%</b> (22%) Oil-Gas= <b>42%</b> (31%) Petroleum= <b>30%</b> (24%) Elec= <b>0.1%</b> (22%) Gas= <b>42%</b> (47%)	$\sigma$ between energy types=0.0 Coal= <b>2.2%</b> Oil-Gas= <b>31%</b> Petroleum= <b>13%</b> Elec= <b>-28%</b> Gas= <b>-3%</b>	Estimates both short-run (capital and labour fixed) and long-run (capital and labour variable) rebound. Distinguishes between primary energy (coal and 'oil-gas') and secondary energy (petroleum, electricity, gas). The lower (negative) estimate of long-run rebound for electricity derives from disinvestment in the electricity supply sector. The Leontief structure for aggregate inputs means there is no scope for substitution between aggregate energy and capital inputs, which should lead

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		energy sectors, and 0.0 in energy sectors					to lower estimates of rebound effects. However, estimates are sensitive to the assumed elasticity of substitution between different energy types within the 'energy nest'. When these are set to zero, gas and electricity rebounds are negative. There is a large difference in rebound between different energy types, with rebound being highest for 'oil-gas'.

## S2 – Other (non-CGE) studies of rebound effects following energy efficiency improvements by producers

Wei, et al. [13]	Dynamic  Global  Regions=8  Sectors=11	(KE,L),M  Elasticities in all sectors: $\sigma_{K,E} = 0.3$ $\sigma_{KE,L} = 0.5$ $\sigma_{KEL,M} = 0.0$	10% in non-energy sectors, implemented with:  a) inelastic labour supply  b) inelastic regional labour supply  c) fully elastic labour supply  d) allowing for adjustments in capital stock	Energy and Carbon emissions  Global	Baseline Energy (Carbon)  76% (81%) 65% (73%) 67% (83%) 68% (90%)  Range 8%-76% (energy) in sensitivity tests	Sensitivity tests for scenario (b) - inelastic regional labour supply  i) $\sigma$ between energy and other commodities in household consumption: =0.0 = 60% (energy)  ii) $\sigma_{KE,L} = 0.0$ = 27% (energy)  iii) (i) and (ii) combined = 8% (energy)  iii) $\sigma$ between energy and other commodities in household consumption=0.025 and $\sigma_{KE,L} = 0.05$ = 21% (energy)	Dynamic CGE model. Baseline scenario for 2011-2040 calibrated to the IEA New Policies Scenario. First three efficiency scenarios are 'short-term', with the efficiency shock being implemented in 2039, and differ in relation to the assumed flexibility in labour supply. Last efficiency scenario is 'long-term' with efficiency improving at 0.38%/year over the full projection period, and assumes a fully elastic labour supply. The long-term scenario leads to an increase in the aggregate capital stock and higher output (GDP). Rebound effects are estimated for both energy and GHGs, and disaggregated by region and sector.  With flexibility in labour supply, long-term rebound is larger than short term rebound. For the long-term scenario, the smallest energy rebound effect is for Brazil (55%) while the largest is for India (78%). Expressed in terms of carbon emissions, the smallest rebound effect is for Russia (74%) while all other regions have rebounds in excess of 90%. In other words, the efficiency improvements are largely ineffective in reducing carbon emissions.  At the sector level, the highest carbon rebound is in agriculture (91%) and the lowest in households (61%). Estimates are highly sensitive to the assumed elasticity of substitution between energy and value-added in production, but less sensitive to the elasticity of substitution between energy and other commodities in household consumption. However, when these elasticities are both set to only 10% of their original values, the rebound effect is still 21%. If substitution is prevented altogether in both production and consumption, the rebound is only 8%.
Zhou, et al. [14]	Static  China  Sectors=135	KL,E,M (Leontief)  Elasticities in all sectors: $\sigma_{K,L} = 0.5$ $\sigma_{KL,E} = 0.0$ (Leontief) $\sigma$ between energy types = 0.5 in non-	5% for each energy type in turn	Energy  Regional	Long-run (short-run): Coal=21% (22%) Oil-Gas=42% (31%) Petroleum=30% (24%) Elec=0.1% (22%) Gas=42% (47%)	$\sigma$ between energy types=0.0 Coal=2.2% Oil-Gas=31% Petroleum=13% Elec=-28% Gas=-3%	Approach and baseline results are identical to Lu, et al. [12]. This extends these results by decomposing the contribution of different sectors to the rebound effect, together with the contribution of output and substitution effects. Finds that substitution effects are more important than output effects, and that changes in household consumption are major contributors to rebound;

		energy sectors, and 0.0 in energy sectors					
Koesler, et al. [15]	Static  Global  Regions=3  Sectors=8	(KL,E),M  Elasticities vary by sector: $\sigma_{KL,E} = 0.15$ to 0.86	10% in: a) German manufacturing sector  b) German production sectors	Energy  Regional and Global	Baseline:  Rebound estimated for: i) German production sectors; ii) Germany; iii) Globally  a) With efficiency improvement in manufacturing sector, rebounds are: <b>i) 48%, ii) 51%, iii) 48%</b>  b) With efficiency improvement in all production sectors, rebounds are: <b>i) 47%, ii) 50%, iii) 47%</b>	Varies $\sigma$ between different commodities in consumer utility function. Only small impacts on the estimated rebound effect.	Investigates the global impacts of efficiency improvements in Germany, and contrasts these with the impacts in Germany itself. Labour and capital are assumed to be mobile between sectors in a region, but immobile between regions. As with regional studies, the global impacts are complex and both reinforce and offset one another. For example, energy efficiency improvements improve the competitiveness of German producers, encourage increased exports and thereby reduce production and energy use in other regions. At the same time, efficiency improvements increase German GDP and average wages, increase domestic demand and imports, and thereby increase production and energy use in other regions. The net result is that the global rebound effect is smaller than regional rebound effect. This suggests that regional studies may overestimate the global rebound effect. However, the difference is relatively small and depends in part upon the energy intensity of German production relative to that in the regions with which Germany trades.
Böhringer, et al. [16]	Static  Global  Regions=8  Sectors=8	(KL,E),M  Elasticities in all sectors: $\sigma_{KL,E} = 0.5$	1% in three aggregate sectors (manufacturing, agriculture and services) and three aggregate regions (China, EU and US) investigated in turn	Energy  Global	Baseline  Manufacturing= <b>65%-75%</b> Agriculture = <b>70%-90%</b> Services = <b>70-75%</b>  Range <b>55% to &gt;110%</b> in sensitivity tests	a) $\sigma_{KL,E} = 0.25, 0.5, 1.0$ = <b>60%, 70%, 105%</b>  b) rebound following efficiency improvement in a single fuel type in the manufacturing sector: Coal= <b>55-57%</b> Elec= <b>60-74%</b> Oil= <b>80-86%</b> Gas= <b>60-70%</b>  c)	Provides estimates of global rebound effect using a multiregional model. Engineering savings are calculated at the global level using an MRIO model, following the approach advocated by Guerra, et al. [6]. Rebound effects by sector and fuel are similar for each of the three regions investigated. Sensitivity tests show that easier substitution leads to higher rebound, but rebound effects are relatively insensitive to energy supply elasticities. Improvements in the efficiency of oil use in manufacturing leads to the largest rebound effects, while improvements in the efficiency of coal use lead to the smallest.  The methodology allows the estimated rebound effect to be decomposed into partial equilibrium effects (substitution and income effects) and general equilibrium effects (sectoral composition, energy market, economic growth, and labour supply effects). The latter allow for adjustments in commodity and factor prices throughout

							the economy. Partial equilibrium effects account for between one half and two thirds of the total rebound.
Du, et al. [17]	China  Sectors=9	(KE,L),M  Elasticities in all sectors: $\sigma_{K,E}=0.3$ $\sigma_{KE,L}=0.91$ $\sigma_{KEL,M}=0.3$	1%, 3% and 5% in construction sector	Energy  Regional	Baseline – 1% improvement  Gas <b>99%</b> Coal <b>91%</b> Oil <b>89%</b> Elec <b>84%</b>	No	Focuses on the construction sector, which is one of the top three energy-consuming sectors in China. The baseline estimates are similar for each level of efficiency improvement and are close to backfire. However, no sensitivity tests are conducted

Notes:

1. The production functions combine inputs into pairs, or 'nests'. For example, a nested production function with capital ( $K$ ), labour ( $L$ ) and energy ( $E$ ) inputs, could take one of three forms, namely:  $K(LE)$ ;  $(KL)E$ ;  $(KE)L$ .  $\sigma_{i,j}$  represents the elasticity of substitution between inputs  $i$  and  $j$  within a nest. For example,  $\sigma_{KL,E}$  represents the elasticity of substitution between the capital-labour composite ( $KL$  - or 'value-added') and energy ( $E$ ).
2. Most studies model improved energy efficiency as a costless, one-off increase in the productivity of one or more energy inputs in one or more sectors. Wei and Liu (2017) also model annual improvements in energy productivity, while Broberg *et al.* (2015) include investment costs in their sensitivity tests.

### S3 - CGE studies of rebound effects following energy efficiency improvements by consumers

Study	Type, Region and no. of production sectors	Nesting structure in production and key substitution elasticities	Energy efficiency improvement(s)	Rebound metric  System boundary	Baseline estimate of rebound effect and Range of estimates in sensitivity tests	Effect of specific sensitivity tests on estimated rebound effect	Comments
Koesler [18]	Static  Germany  Sectors= 18	(KL,E),M  Elasticities vary by sector: $\sigma_{KL,E} = 0.15$ to 0.86	10% in the energy efficiency of private transport  a) Inflexible consumption  b) Flexible consumption	Energy  Regional	Baseline:  a) -5%  b) 49%		The utility function includes a private transport nest (a CES function of transport energy and transport materials), which combines with public transport in a transport services nest. The 'inflexible' consumption scenario has a Leontief structure in both of these nests, (preventing substitution between the inputs), while the 'flexible' consumption scenario has an elasticity of substitution of 1.0 between transport services and non-transport goods and services, and an elasticity of substitution of 0.42 between transport energy and transport materials (allowing considerable scope for substitution). The results suggest that the economy-wide rebound is less than the rebound effect for households alone, owing to reduced output from energy-intensive sectors. A decomposition analysis suggests that the direct rebound effect is three times larger than the indirect effect. Inertia in household responses will reduce the size of these effects, but only the long-term rebound is reported here.
Lecca, et al. [19]	Dynamic  UK  Sectors=21	(KL,E)M  All sectors: $\sigma_{E,M} = 0.3$ $\sigma_{KL,EM} = 0.3$ .	5% in household energy efficiency  a) $\sigma$ between energy and non-energy goods in consumption =0.35  b) $\sigma$ between energy and non-energy goods in consumption = 0.61	Energy  Regional	Baseline  a) Short run=40%  b) Short run=69% <b>Long run= 64%</b>		The results demonstrate that easier substitution between energy and non-energy goods in household consumption lead to a higher estimate of the rebound effect. The low estimate of this elasticity is interpreted as a short-run value, while the high estimate is interpreted as a long-run value (after investment in consumer durables are taken place and after inertia in consumer-decision-making has been overcome). As a result, the long-run rebound is only estimated for the high estimate of this elasticity.  The results also suggest that the long-run rebound is less than the short run, owing to disinvestment effects.

Figus, et al. [20]	Dynamic  Scotland  Sectors=21	KL,EM  All sectors: $\sigma_{E,M} : 0.3$ $\sigma_{KL,EM} : 0.3$ .	5% in household energy efficiency  a) Fixed labour supply, standard CPI  b) Flexible labour supply, standard CPI  c) Fixed labour supply, adjusted CPI  d) Flexible labour supply, adjusted CPI	Energy  Regional	Baseline  Scenario a) Short run= 28% Long-run = <b>50%</b>  Scenario b) Short run= 27%% Long-run = <b>50%</b>  Scenario c) Short run= 31% Long-run = <b>63%</b>  Scenario d) Short run= 28% Long-run = <b>78%</b>		Household efficiency improvements increase aggregate demand, increase domestic prices, crowd out exports, and reduce the competitiveness of the Scottish economy. The four 50-year scenarios explore this effect and its sensitivity to two variables that influence the impact of efficiency improvements on competitiveness: 1) the flexibility of labour supply; and 2) the extent to which efficiency improvements reduce the cost of living. Having a flexible labour supply (through inward migration) puts downward pressure on wages and prices, restores competitiveness in the long-term and increases GDP growth. Similarly, reductions in the cost of living from the efficiency improvements (modelled by reducing the consumer price index) also increase competitiveness. If the negative impact on domestic competitiveness is reduced, the efficiency improvements will provide a greater boost to economic output and hence a larger rebound effect.
Kulmer, et al. [21]	Static  Austria  Sectors = 45	(KE,L),M  Vary by sector  Not specified	10% in efficiency of fossil fuel use by households	Energy  Regional	Baseline <b>65%</b>  Range <b>59% to &gt;73%</b> in sensitivity tests	In the baseline scenario, each of six types of household has different assumptions for the substitution elasticities between: a) energy commodities (0.4 to 0.65); and b) energy and other goods (0.25 to 0.40)  In the sensitivity tests, these elasticities are randomly varied between 0.1 and 1.2 (80 runs in total)	Static analysis, assuming capital and labour are mobile and fully employed. Efficiency improvements are confined to fossil fuel use by household, so there is some substitution towards electricity. Unusually, the study distinguishes six types of household - differentiated by car ownership, urban versus rural, children and employment status. The direct rebound effect is relatively modest in the baseline scenario (8.0-12.5%), so most of the rebound derives from indirect and economy-wide adjustments. Efficiency improvements provide a small boost to GDP and wages, and redistribute household expenditure, including increased consumption of energy-intensive goods such as food and transport.  The study includes a systematic, Monte Carlo analysis of the sensitivity of the results to the assumed elasticities of substitution between: i) different energy commodities; and ii) energy and other goods and services within the consumer's utility function. The more easily households can substitute between different energy commodities, the higher the rebound - with a larger impact on direct rebound (2-30%) than on economy-wide rebound (60-73%). Rebound estimates are less sensitive to the elasticity of substitution between energy and non-energy goods. In the baseline scenario, the rebound can be

							neutralised by a tax of 43% on household fossil fuel use, while in sensitivity tests the required tax rate varies between 15% and 80%.
Duarte, et al. [22]	Dynamic Spain Sectors =34	(KE,L),M  Vary by sector $\sigma_{K,E} = 0.1$ to 0.9 $\sigma_{KE,L} = 0.1$ to 0.9	a) 20% reduction in household electricity use by 2030, relative to 2005  b) 20% reduction in household vehicle fuel use by 2030, relative to 2005  c) a and b combined	Energy Regional	Baseline (2030):  a) Elec= <b>71%</b> ; All energy= <b>51%</b>  b) Road fuel= <b>51%</b> All energy= <b>52%</b>  c) Elec+Road Fuel= <b>56%</b> All energy= <b>75%</b>	a) $\sigma$ between electricity and fuel in consumption function  b) $\sigma$ between road fuel and transport services in consumption function	Models a costless improvement in energy efficiency between 2005 and 2030, with the rate of improvement following a Gompertz curve to reflect technology diffusion. The level of improvement in each scenario is that required to deliver the quantity target for household energy consumption after allowing for rebound effects. This, in combination with the projected economic growth to 2030, leads to a required ~80% improvement in household energy efficiency (which could be difficult to achieve). In scenario (c), the associated reduction in economy-wide energy consumption is only 6%. The estimated rebound effects increase as the economy adjusts throughout the projection period. The study explores the sensitivity of the results to the elasticity of substitution in production, but does not quantify the associated rebound effects.
Bye, et al. [23]	Dynamic Sweden Sectors=41 Goods=18	(KE,L),M  Vary by sector $\sigma_{K,E} = 0.1$ to 0.9 $\sigma_{KE,L} = 0.1$ to 0.9	a) 27% reduction in household energy use by 2030, relative to baseline scenario  b) 27% reduction in household energy intensity by 2030, relative to baseline scenario	Energy Regional	Baseline  Electricity: a) <b>37%</b> b) <b>40%</b>	$\sigma$ between energy and 'dwellings' in the consumption function  i) 0.0 ii) 0.3 iii) 0.6  = i) 17%; ii) 37%; iii) 62%	The study compares two efficiency scenarios against a baseline scenario for 2030. The latter meets the Swedish emission targets and includes carbon pricing. The efficiency scenarios incorporate a constraint on household energy use (intensity), which is in addition to the budget constraint in the consumers utility maximisation problem.. These constraints provide a shadow price equal to the estimated marginal costs of the efficiency improvements. In the baseline scenario, this shadow price corresponds to a ~175% increase in energy prices. The baseline is assumed to include negative cost efficiency measures, so these are excluded from the efficiency scenarios.  The study estimates rebound effects for electricity, which accounts for 90% of Norwegian household energy consumption. The inclusion of capital costs means that direct rebound effects are small: instead, the main driver of the economy-wide rebound is the fall in electricity prices.  The estimated rebound effect is sensitive to the assumed elasticity of substitution between energy and dwellings in the consumption function. This parameter is a measure of the cost of energy efficiency investment, and influences the shadow price of the constraint.

							It is interesting to note that the projected rebounds are large, <u>despite</u> allowing for the capital cost of the efficiency improvements. In addition, both scenarios project an <u>increase</u> in carbon emissions relative to the baseline. This is partly a consequence of the Swedish electricity supply mix (which is largely hydro and hence low carbon), but also derives from the inclusion of process emissions.
Barkhordar [24]	Dynamic  Iran  Sectors = 10	Not stated	Adoption of energy efficient lighting by Iranian households –	Energy  Regional	Baseline  Mean rebound effect: <b>44%</b>  Simulates the evolution of the rebound effect over time. Rises to a peak of ~52% within three years, then slowly falls to ~35% in 2040.		Compares BAU and 'efficient lighting' scenarios to 2040. The latter is expected to reduce electricity consumption for household lighting by 63%. A notable feature of the model is that consumer utility functions are specified for energy services (e.g. lighting, water heating), rather than energy commodities.  The initial direct rebound effect for households alone is 28%. Efficiency improvements lower electricity demand and reduce electricity prices - which in turn increases the quantity of electricity demanded by households and leads to a rebound effect for households of 47%. Income effects encourage increased consumption of other goods and services, leading to increased production, higher value-added, higher wages and increased household income that in turn is spent on more goods and services goods. These raise the economy-wide rebound effect. However, over time the capacity of the electricity sector contracts (disinvestment), leading to a rise in electricity prices and a reduction in the economy-wide rebound.

Notes:

1. The production functions combine inputs into pairs, or 'nests'. For example, a nested production function with capital (K), labour (L) and energy (E) inputs, could take one of three forms, namely: K(LE); (KL)E; (KE)L.  $\sigma_{ij}$  represents the elasticity of substitution between inputs i and j within a nest. For example,  $\sigma_{KL}$  represents the elasticity of substitution between the capital-labour composite (KL - or 'value-added') and energy (E).
2. Most studies model improved energy efficiency as a costless, one-off increase in the utility obtained from one or more energy commodities in the consumption bundle. Duarte, et al. [22] also model annual improvements, while Bye, et al. [23] incorporate a shadow price on energy efficiency.

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