Can we retain the economy-wide benefits of energy efficiency while reducing the energy rebound?

Lisa Ryan, Energy Institute, University College Dublin
Karen Turner and Gioele Figus, Centre for Energy Policy, University of Strathclyde
Nina Campbell, Databuild
Patrizio Lecca, Peter McGregor and Kim Swales, Department of Economics, University of Strathclyde

Making a difference to policy outcomes locally, nationally and globally

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Abstract

Economy-wide rebound is often presented as a necessary 'evil' accompanying economic expansion triggered by energy efficiency improvements. We challenge this position in two, inter-related ways. First, we question the emphasis on potential technical energy savings and losses due to rebound in energy efficiency policy evaluation. This abstracts from the wider economic and societal impacts of energy efficiency improvements that are often positive and valuable to policy makers. Second, we propose that economic expansion and economy-wide rebound need not be highly correlated. We argue that energy efficiency actions targeted at improving the competitiveness of less energy-intensive means of providing services, such as heat and transport, may provide opportunities to boost economic activity while minimising rebound effects. This perspective involves a change in current policy and research thinking, particularly in terms of the type of substitution possibilities that we should focus on in enhancing energy efficiency, economic expansion and rebound relations.

1. Introduction

Improvements in energy efficiency have historically been promoted as a cost-effective and efficient way to reduce energy demand and greenhouse gas emissions (IEA, 2015; UNEP 2014; European Commission, 2014). Energy efficiency measures play a key role in many countries' strategies to mitigate climate change, while improving the security of energy supply in so much as it reduces pressure on the demand for energy. However, the benefits are not limited to energy and greenhouse gas emission savings. There is a wider set of potential benefits from improving energy efficiency that are now being coined 'the multiple benefits of energy efficiency' (IEA, 2014; ACEEE, 2015). These benefits extend from individual level to national and regional level and across economic, social and environmental contexts. Notwithstanding this, the merit of energy efficiency as a mitigation measure is regularly called into question in both academic and popular press with allusions to 'the rebound effect' (*e.g.* see Revkin, 2014). Rebound occurs when the realised reduction in energy demand is less than the engineering estimates would predict because of a range of economic responses triggered by the initial reduction in energy service price faced by the more efficient user.

There is an inherent tension in considering rebound as an indicator of the success or not of energy efficiency policy while adopting a multiple benefits prism. The measurement of rebound generally focuses on the ratio between actual and potential energy savings, where the latter is given by pure engineering savings that are technically possible. To have zero rebound in this setting would imply the absence of *any* economic response to a change in efficiency. This would seem to be a perspective peculiar to the energy efficiency-rebound literature and not one that would enter consideration of increased efficiency in, for example, the use of capital or labour. The multiple benefits prism, on the other hand, views the desired energy demand reduction as but one vector of many outcomes of energy efficiency policy measures (albeit the primary and thus potentially most heavily weighted objective).

In this paper we examine the nature of economy-wide impacts of energy efficiency improvements more closely and the relationship with rebound effects. We argue that it is necessary to consider whether rebound in an economy-wide perspective reflects an outcome that is welfare-enhancing from a societal perspective or whether rebound implies outcomes that are sufficiently negative (in terms of lost energy savings) to either deter from energy efficiency improvements or to warrant 'rebound mitigation' policy actions. However, we then go a step further, considering whether it might be possible to reduce economy-wide rebound effects (maximise energy savings) while retaining the welfare gains of energy efficiency improvements, without resorting to mitigation tactics (such as additional tax burden associated with energy use) that may both constrain expansion and exacerbate inefficiencies/distortions in the economic system. We do so by considering the hypothesis that it may be possible to reduce rebound by focussing energy efficiency improvements on activities that are substitutes for more energy and/or carbon intensive competitors in delivering energy-using services such as transport, electricity, and heating. This introduces a different focus in terms of the types of substitution possibilities that have played such an important role in the rebound literature, traditionally with high inter-fuel and energy/non-energy substitution elasticities being associated with large rebound effects. Rather our argument relies on increasing substitution probabilities between different means of delivering services to favour less energy and/or carbon-intensive options.

This paper is structured as follows. Section 2 considers the policy context for concerns over rebound effects. Section 3 then aims to clarify the different types of expansionary processes associated with energy efficiency improvements that give rise to economy-wide rebound and the traditional consideration of substitution possibilities in this respect. Section 4 focuses on the relationship between economy-wide rebound effects and socio-economic welfare. Section 5 then presents the results of an illustrative CGE modelling exercise to elucidate our arguments regarding how economy-wide rebound may be minimised without sacrificing macroeconomic benefits (through exploiting substitution possibilities, here between different means of delivering transport or mobility services). Finally, we conclude in Section 6 with some implications for policymakers and considerations for future research.

2. Why are we concerned about rebound effects?

A basic definition of an energy efficiency improvement would be enabling the use of less physical energy (e.g. gas) to provide the same service output (e.g. hours of heating at a given temperature) and, consequently, at a lower cost. This is the trigger for economic rebound at various (direct, indirect and economy-wide) levels.

It is useful to begin by examining the objectives of energy efficiency policy and an overview of the recent academic literature on rebound in order to better understand how rebound effects impact the achievement of these objectives.

Many improvements in energy efficiency are designed as cost-effective measures to reduce energy consumption while addressing energy security, environmental and economic challenges. Improvements in energy efficiency can also lead to a reduction in the need for investment in energy infrastructure, fuel costs, as well as increased competitiveness and improved consumer welfare. Energy efficiency is widely considered as a key tool, particularly in addressing climate change. For example, IEA models estimate that in order to reduce CO_2 emissions by half in 2050, energy efficiency would need to account for approximately 40% of the total emissions reductions in 2050 (IEA, 2015).
However, despite high potential for energy savings across most economies, there exist several barriers and market failures that limit investments to enable and/or uptake of improvements in energy efficiency (IEA, 2007; Ryan *et al*., 2011; Sorrell *et al*, 2004). There is a growing literature on how governments must carefully design and implement energy efficiency policy instruments to address market failures in the uptake of energy efficiency (the so-called “energy efficiency gap”, Jaffe *et al*., 2005; Gillingham and Palmer, 2014; Gerarden et al., 2015a, b).

The successful realisation of energy efficiency policy objectives is usually measured by the reduction in energy consumption and GHG emissions attributed to the energy efficiency policy. Cost-benefit analysis of energy efficiency policy tends to include the costs of implementing the policy, such as the total outlay on incentives, the administrative costs, and enforcement costs where appropriate, while the estimation of benefits generally focuses only on the value of the energy savings and of the GHG emissions reduced (as calculated on the carbon market at that moment in time). In this context, the concept of rebound has manifested in recent years as another less tangible barrier to at least the perception of potential effectiveness of energy efficiency innovations and policy.

Academic literature on rebound has been growing over the last twenty to thirty years. This was triggered by the contributions of Brookes (1978) and Khazzoom (1980) building on much earlier foundations laid by Jevons (1865). In recent years, perhaps triggered by policy attention to the potential implications of rebound (e.g. UK House of Lords, 2005; Maxwell et al., 2011), and well-known review works such as the UKERC study edited by Sorrell (2007) and the Breakthrough report of Jenkins et al. (2011), the rebound debate seems to have exploded. Attention has extended from basic direct rebound measures (the response of an energy user to the reduction in cost of an energy service when the efficiency of its delivery improves) to economy-wide rebound. The latter is broadly defined in terms of changes in all types of energy use across the whole economy triggered by the chain of economic reactions to a specific energy efficiency improvement in a given sector of the economy set against the potential energy savings associated with that efficiency improvement.

The rebound literature can be divided into studies (i) reporting empirical measurements of mainly direct rebound effects (*e.g.* Saunders, 2014, 2015; Small and van Dender, 2007); (ii) reviews of rebound effect estimates (Sorrell *et al*., 2009; Greening *et al.,* 2000; Gillingham *et al*., 2014); (iii) discussions of theoretical frameworks for rebound (e.g. Saunders, 2014; Howarth, 1997); and (iv) categorising different types of rebound effects (van den Bergh, 2011; Turner, 2013; Borenstein, 2015). One key problem for policy and wider understanding of the rebound issue is a lack of transparency in and common ground across many studies in how rebound is actually measured (at all levels, but particularly beyond the direct level).
While the basic definition of rebound as one minus the ratio of actual energy savings to potential energy savings (converted to percentage terms) is widely accepted, there is less clarity in terms of how actual and potential energy savings are actually measured in different studies. In particular, there is often a lack of clarity in terms of whether the focus is on impacts of the pure efficiency improvement alone or with other 'baseline' scenario considerations, such as quantity adjustments in the energy supply chain directly serving more efficient users (see Guerra and Sancho, 2010; Turner, 2013).

A fundamental problem may lie with the inherent perspective in the rebound literature – and, crucially, how it is interpreted - that anything less than a full realisation of potential technical/engineering savings in energy use implicitly raises questions in terms of the effectiveness of energy efficiency enhancing instruments. This is a questionable perspective. For example, we do not expect or want labour efficiency improvements to lead to an erosion of employment. Rather, we expect economic responses to lead to an (efficient) expansion of (more productive) economic activity. Why then would we expect (or desire) economic actors to be unresponsive to the stimuli produced by an improvement in efficiency in energy use? The key difference in the context of the labour efficiency comparator would seem to be that public and politicians alike would welcome large rebound, ideally backfire[1] effects in employment. Indeed, this is likely to be a primary aim of economic policy built around labour efficiency improvements. On the other hand, any energy efficiency policy action that results in a net increase in energy use may be viewed as somewhat counter-productive (though empirical evidence suggesting likelihood of such a 'backfire' even at economy-wide level in the case of energy efficiency is limited).

It may also be argued that the definition and measurement of a single 'rebound' measure is in danger of becoming a distraction from actually understanding and explaining how energy efficiency improvements work and impact on a full range of activities and agents in the wider economy in different case study and policy contexts (Turner, 2013). It would seem more important for policy purposes to clearly report and explain a full range of both increases and decreases in energy use in different sectors of the economy. Moreover, this should be considered in the context of both economic and social benefits (e.g. increased income in low income households) and costs (including, as well as rebound, contractions in activity and employment in energy/fuel supply activities) that accompany (or are accompanied by) changes in energy use. Perhaps more crucially, analysis of different rebound pressures must be presented and explained in such a way as to permit policy makers to consider how/if they need to address 'the problem'. This perspective is aligned with the assertion by Gillingham *et al.* (p. 26, 2014):

"*Rather than consider the rebound effect as a deterrent from passing energy efficiency policies, policymakers should include [these] welfare gains in the tally of benefits of a policy. The mistake of designing policies to "mitigate" the rebound effect stems from a focus on minimising energy use, rather than the broader objective of maximising economic efficiency*."

Put simply, the success of energy efficiency improvements in delivering energy savings should be considered in the context of the full range of multiple benefits or indicators that are of interest to government as representing the interests of society. These include energy prices, security and poverty, along with GHG emissions, a range of macroeconomic indicators such as GDP, employment and public budgets, as well as 'health and well-being'. The energy efficiency literature provides numerous examples where one or more of these parameters have been estimated and found to be positive and significant (ACEEE, 2014; Copenhagen Economics, 2012; Diefenbach *et al*., 2014; Howden-Chapman *et al.,* 2009; Janssen and . Staniaszek, 2012; Kuckshinrichs *et al.*, 2013; Lehr *et al.,* 2013; Liddell and Guiney, 2014; Worrell *et al.,* 2003) but rarely are they comprehensively included in government policy evaluation.

[1] Backfire is when the rebound is greater than 100%

Generally, while cost-benefit analyses for energy efficiency policies may include rebound as a 'cost' via reduced energy and GHG emissions savings, the non-energy benefits that may give rise to rebound effects tend not to be included. Moreover, broad estimates of overall rebound are generally considered as more of a qualification on expected energy savings rather than properly analysed. This also tends to be true of the potential economic and social costs that may result from reduced demand for/activity in energy production.

This relatively narrow frame of assessment employed in evaluating policies in many countries can attribute undue importance to rebound effects by underestimating the benefits of the energy efficiency measure (Ryan and Campbell, 2012; IEA, 2014). It is thus important to understand the wider non-energy impacts of an energy efficiency measure and the relationship with a consequent change in energy consumption (*i.e.* the rebound effect) in order to be able to assess the full value of energy efficiency measures. Moreover, a key question from a policy standpoint is likely to be whether welfare can be further maximised while reducing (or at least not increasing) economy-wide rebound.

3. The Macroeconomic Impacts of Improvements in Energy Efficiency

The multiple benefits of energy efficiency improvements include macroeconomic impacts as reflected in changes to key variables such as GDP, incomes, employment and trade.[2] The IEA (2014) identify two distinct stages that will trigger impacts at the macroeconomic levels: (i) investment in efficiency-enhancing technology; and (ii) the realisation of efficiency improvements, although in practice the two steps may occur almost simultaneously with interacting impacts.

Let's take these in turn. In many cases the first action taken as part of an energy efficiency measure is to invest in energy-efficient goods and/or services.[3] Investment spending, as well as enabling efficiency improvements, introduces additional demand along supply chains servicing this spending, which will lead to expansion involving energy use in different parts of the economy. However, as with any demand-led expansion, where there are constraints on supply this may impact prices and potentially 'crowd out' other activities.

[2] The term macroeconomic in this paper is used to cover economy-wide effects that occur at national, regional and international level. It is concerned with the aggregate effects of energy efficiency measures which may be considered as comprising (i) the sum of the individual microeconomic effects, and (ii) the impacts of the whole economy resulting from non-linear complex interactions throughout the economy.

[3] Energy efficiency improvements can also be undertaken without involving investment if we assume energy efficiency improvements are delivered as a public good, in which case only the energy cost reduction effects apply in this discussion. However, for large scale improvements in energy efficiency needed to optimize energy efficiency potential globally, both behavioural change and investment – as well as investment financing systems that encourage behavioural change - will be needed. Therefore the investment effect will apply for most governments seeking to estimate the macroeconomic effects of energy efficiency measures.

The ‘second step’ arises in that when a more energy efficient technology is used and the physical energy use required per unit of production of consumption activity falls, then more efficient users should enjoy reduced costs in delivery of the energy service in question. At this point, individuals or businesses will achieve real income increases and make decisions on reallocating savings on energy bills. However, as argued by Turner (2013) and Lecca *et al.* (2014), the nature of the subsequent wider economic expansion is likely to differ depending on the broad type of use where efficiency improves, of which we identify two.

First, where efficiency occurs in household energy use (i.e. the final consumption side of the economy) as with the investment stage above, this is the source of a demand-driven expansion in economic activity. Again, the net direction and magnitude of the impact on macroeconomic indicators will depend on the nature of spending, supply and fiscal conditions and the impacts on prices and competitiveness. Similarly, the qualitative and quantitative nature of indirect or economy-wide rebound effects will vary, particularly where reduced energy demand leads to contraction in capacity and activity in energy supply chains (Turner, 2009, 2013).

On the other hand, where an efficiency improvement takes place on the production side of the economy the successful implementation of energy efficiency enhancing technology will trigger a productivity-led, or cost-push expansion where a clearer path to net positive impacts on key macroeconomic indicators may be more unambiguously anticipated. While the extent and dynamics of expansion (and related energy use) will depend on the specific nature of the efficiency improvement and on capacity and conditions particularly in labour and capital markets, the *net* impact on all components of GDP has the potential to be positive. However, even where net positive impacts are likely to occur at a macro level, the *gross* impacts at sectoral level may not all be positive. As above, where there is a net decrease in energy use, there may be a contraction in activity and capacity in energy supply sectors, while, more generally, labour and capital supply conditions will govern the extent to which different sectors are able to expand. The greatest pressure for expansion is likely to occur in sectors that are impacted (directly or indirectly) by the initial efficiency improvement (through supply chain linkages). However, these will not necessarily be sectors that produce the most value-added for the economy, or employ the most people/provide the most income from employment, and they may be more or less energy and/or carbon intensive sectors.

What about economy-wide rebound effects accompanying expansionary processes in either of these two (broad) cases? In the major UKERC review of rebound evidence reported in Sorrell (2007), economy-wide rebound findings, mainly from studies using CGE modelling techniques, took on a wide range of values. A key conclusion was that economy-wide rebound is dependent on the nature and location of the energy efficiency improvement and the economic conditions prevailing in the economy under study. The findings of more recent CGE studies (e.g. Lecca et al. 2014; Broberg *et al*., 2015) continue to support this conclusion. Case-specific conditions include a range of factors, particularly costs of introducing efficiency improvements, energy intensity of the sector where efficiency improves, and how the labour market functions.

However, Turner (2009) – and the sensitivity analyses of many CGE modelling studies – demonstrates that the assumed or estimated values assigned to key substitution elasticities play a key role in governing the extent of *both* economic expansion *and* economy-wide rebound. This is particularly in the production/consumption functions of sectors where energy efficiency improves and/or where more efficiency outputs are used. Rebound researchers (both CGE and more generally) have focussed on the importance of the importance of (a) inter-fuel substitution elasticities; (b) elasticities of substitution between energy and materials/non-energy goods (in consumption and production), energy, capital and labour (just production); (c) trade elasticities for energy and energy-using goods and services. All other things held constant, the higher these elasticities are, the greater will be both any expansion and the economy-wide rebound effects triggered by an efficiency improvement.

Consequently, rebound mitigation propositions have tended to focus on constraining substitution effects, in particular by countering the initial decrease in the effective and/or market price of a particular energy type following the efficiency improvement itself and/or the consequent demand reduction. However, such actions would be likely to also constrain the expansionary process itself, which will have wider welfare implications in terms of lost opportunities from energy efficiency policies.

Moreover, to date the rebound literature has not addressed the question of whether economic expansion and economy-wide rebound need be so closely tied following an energy efficiency improvement. This is an important gap. If it can be filled, well-informed policy analysts may look to target energy efficiency improvements so that they facilitate (rather than constrain) consequent expansionary processes in areas of the economy where such processes give rise to benefits (e.g. increased employment). Moreover, where this may involve efficiency-induced stimuli favouring lower energy/carbon-intensive activities that are competitors for more energy/carbon-intensive ones in delivering services, well-aimed policy action may involve acting to enhance rather than constrain substitution possibilities.

4. Economy-wide Rebound Effects and Welfare

A central question considered in this paper is how to enhance the relationship between energy efficiency policy, economy-wide rebound effects and societal welfare. More specifically, we focus on the question of whether it is possible to consolidate welfare gains while limiting the energy rebound (or maximising energy savings). In this context, we understand welfare to include a wider societal utility, represented by economic prosperity but also societal values as associated with health and wellbeing, environment and climate change mitigation, employment, and social equality. That is, the basic interpretation of the term 'multiple benefits' proposed in IEA (2014). We consider this perspective by examining first the link between welfare improvements at economy-wide level from energy efficiency measures and rebound and then the factors that determine the size of the resulting economy-wide rebound.

4.1 Rebound and welfare effects from increased energy efficiency

There has been little analysis of the relationship between energy efficiency, welfare and rebound in the academic or policy literature, with few examples of explicit estimations of the welfare impacts from rebound effects. Several papers acknowledge that the energy efficiency rebound effect is likely to have positive welfare implications (Gillingham et al., 2014, Borenstein, 2015) but this assertion has not yet been explicitly examined for the economy-wide case in any detail.

Chan and Gillingham (2015) provide the first welfare-focused treatment of the rebound at the *microeconomic* level. They use a theoretical model of consumer utility to derive conditions when rebound is likely to generate overall welfare gains. It does not include the costs of investment in energy efficiency, nor the dynamics or behavioural anomalies of the decision process. They show that, when there are external costs present, an 'exogenous costless increase' in energy efficiency and the consequent direct and indirect rebound may increase or decrease welfare. The determining factor in Chan/Gillingham model is the external costs associated with increased energy consumption. If these are lower than the benefits from increased energy use through the rebound effect, then the rebound effect is welfare enhancing. This approach implicitly assumes that we do not consider the sole objective of energy efficiency policy to be energy savings but rather to be overall economic efficiency and societal welfare, as is true of in policy making in other areas such as labour and health.

How do we move from this to consideration of the welfare implications of economic expansion accompanied by rebound at the economy-wide level? If we were to apply a similar approach as Chan and Gillingham (2015), a detailed analysis and good comprehension of *societal* costs and benefits arising via the economy-wide response would be needed. If the primary objective of energy efficiency policy is to reduce energy use then this should be weighted accordingly in policy assessment among the broad set of potential policy outcomes.

4.2 Boosting the energy rebound / welfare relationship

In Section 3 we have discussed how improvements in energy efficiency will drive demand-led or productivity-led (cost-push) expansions in economic activity, but with supply conditions determining whether this will involve crowding out and/or reallocation of labour and capital between different sectors. Depending on the nature of production in the sectors that benefit most in the expansionary process, increased activity in any one sector is likely to be accompanied by some increase in energy use/energy rebound with associated external costs in that sector and potentially elsewhere. On the other hand, particularly in more labour and/or wage-intensive expanding sectors, these costs will occur alongside increases in employment and income from employment. These are two economic variables that are generally considered to be welfare-enhancing (e.g. see Whelan et al. 2015).

Thus, a first point of interest in assessing whether costs associated with energy rebound are likely to dominate benefits from economic expansion may be whether the expansionary process favours more or less energy-intensive sectors as against (and/or or combined with) other characteristics such as labour- and/or wage intensity. That is, considering the likely *composition* of increased economic activity and the extent to which it will deliver social benefits that may be set against the costs associated with accompanying economy-wide rebound effects.

However, a second question is whether it is possible to design and target energy efficiency policy in such a way that the delivery of socio-economic benefits can be decoupled from economy-wide rebound effects. We put forward the following hypothesis. If energy efficiency improvements can be targeted at a means of delivering an energy using service (e.g. public transport) that is a substitute for a more energy-intensive competitor (e.g. private transport in delivering, e.g. miles per person), and it is possible to make the less energy-intensive option more attractive to service users, then such a decoupling may be possible. In other words, we propose targeting energy (and potentially other types of) efficiency improvements in a way that exploits substitution possibilities between different means of delivering energy-using services so as to favour relatively low energy/carbon options, thereby limiting the energy rebound potential of welfare-enhancing economic expansion.

Exploring this hypothesis requires a broadening of our attention from one of the mainstays of rebound research, namely the focus on rebound occurring through substitution effects that favour increased but more efficient energy use. New focus is required to consider not just energy use itself but the inputs to the production of energy services, which will be more or less directly *and* indirectly energy-intensive. Crucially, it also involves focus on how service users respond to changes in price and other determinants of demand in the competing options they may choose between. For example, in choosing between electricity- rather than gas-powered heating systems (assuming that electricity is delivered in a low carbon way), or between different modes of public transport relative to fuel use in private cars to deliver mobility.

This service-focused argument may not be an immediately intuitive one for policy making, where the most energy-intensive production and consumption processes have generally been the first targets of energy efficiency policies (i.e. heavy manufacturing, inefficient lighting, driving private cars; see IEA 2011). Moreover, it is one that requires considerable research effort. As discussed above, the economic channels for the economy-wide impacts of energy efficiency and resulting rebound are strongly case-specific. Similarly, empirical analysis of different case studies for different types of service delivery in different economic conditions would be required in order to establish the conditions for which our hypothesis might hold and to determine how it might be exploited to further enhance the net welfare gains of energy efficiency measures. In the next section we provide a simple illustrative example of how the conventional CGE modelling approach to assessing economic expansion and economy-wide rebound may be applied in this respect.

5. Results from an illustrative economy-wide impact analysis of energy efficiency improvements in transport activity

To illustrate the hypothesis suggested above, we consider the potential impacts of a simple scenario of an energy efficiency improvement in the provision of public transport in the UK. We adopt the method most commonly applied in the literature to assess economic expansion and economy-wide rebound, with a simulation exercise using a multi-sector computable general equilibrium (CGE) model of the UK economy. However, we emphasise that the example and simulation work is kept very simple at this stage and should be taken as more of a numerical experiment with a basic model to elucidate our argument rather than a policy simulation exercise.[4]

The model we use is UKENVI, a recursive dynamic CGE model designed to analyse environmental and energy disturbances in a multi-sectoral economy-wide national setting, and one that has previously been used in rebound studies such as Turner (2009) and Allan et al. (2007). Following the approach of Anson and Turner (2009), we introduce a broad-brush 10% increase in energy efficiency in the UK 'Road and Rail Transport' industry, which incorporates both freight and passenger transport.[5] To keep things simple, the efficiency improvement is introduced as an exogenous and costless step increase in energy-augmenting technological

[4] Where there is potential policy interest in a wider set of cases aimed a exploiting substitution possibilities between different ways of delivering energy using services such as heat and transport, it will be an appropriate focus for future modelling work to focus more carefully on just how energy efficiency improvements may be introduced – including issues of infra-structure requirements - as well as how resulting cost savings may or may not translate to changes in the price of output/competitiveness (depending on how markets actually function) and/or other determinants of service demand.

[5] This industry classification is given by the UK input-output data used as the main part of the structural database of the model, where both passenger and freight activity are included in road and rail transport sectors. However, household consumption will be mainly on the passenger side while improved efficiency on the freight side will have positive competitiveness effects downstream in UK industry.

progress in the use of energy as an input to production (i.e. the same output is produced using 10% less physical input of energy). Some key details of the model are given in Appendix 1.

The key macro-level impacts of the energy efficiency improvement are reported in Table 1. Here we report results for two conceptual time frames: the short run (where capital stocks are fixed); and the long run (where the capital stock is fully adjusted). In all time frames we assumed a fixed national stock of labour but with some flexibility in labour supply through a pool of unemployed labour. Results are reported in terms of percentage change from the base line given by the SAM (i.e. we focus on the impacts of the single shock simulated relative to an unchanging base case in order to isolate the impacts of the pure energy efficiency improvement).

The results in Table 1 reflect a cost-push or productivity-led expansion in the UK economy. An increase in energy efficiency in this one production sector equates to a small but positive supply-side shock. Given the illustrative nature of the simulation, the qualitative nature of the results in Table 1 is the key thing to consider. From the outset, but to a greater degree over the long-run, key macroeconomic indicators such as GDP, aggregate investment, household income, exports, government deficit, employment and the unemployment rate all 'move in the right direction' from the multiple benefits perspective proposed in IEA (2014). Total energy use in UK production falls, though Figure 1 shows that gross decreases in energy use are observed only in energy supply chain sectors, with these accompanying contractions in output as demand from the Road and Rail industry falls with increased efficiency. As the economy expands (coupled with some decrease in UK energy sector prices in response to decreased demand), energy use rises with (and in some cases more than) output in other sectors and in households. However, the net impact is a decrease in total UK energy use and, from the outset, this is set against increasing GDP to deliver an increase in the 'energy productivity' of the UK economy. Over the long-run household income rises more than energy use so that this basic indicator of 'fuel poverty' also moves in the right direction.

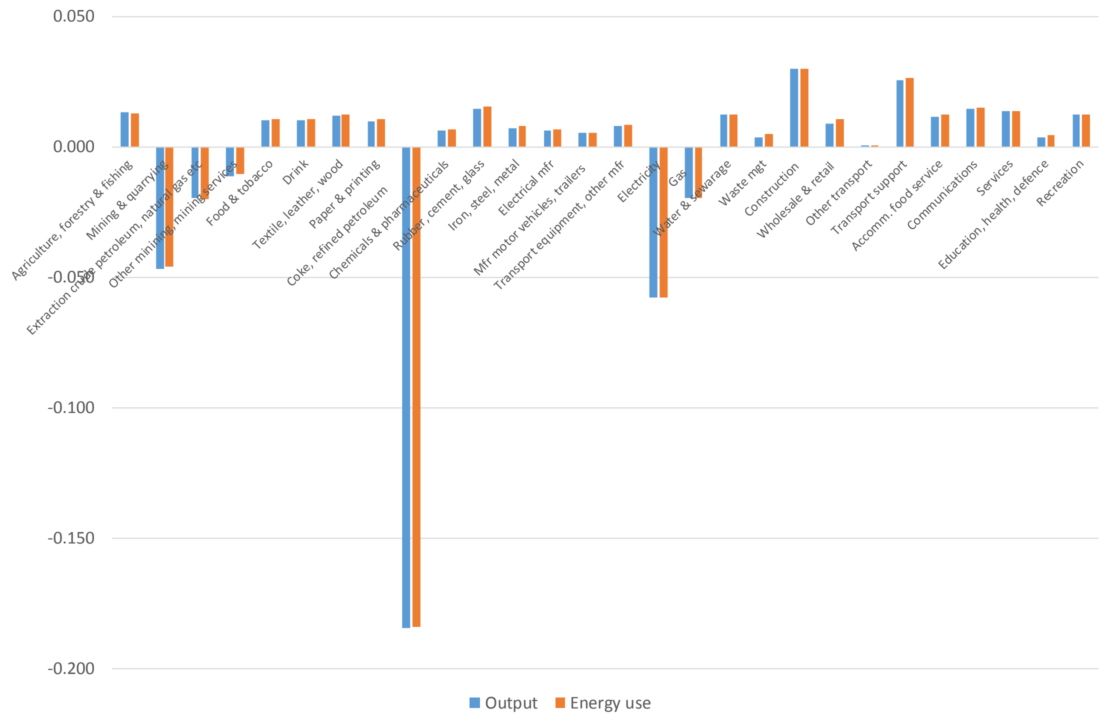
Table 1: Macro-level impacts of a 10% increase in energy efficiency in UK 'Road and Rail ' industry (% change from base)

	Short run	Long run
GDP	0.004	0.011
Consumer Price Index	0.005	-0.007
Unemployment Rate	-0.102	-0.146
Total Employment	0.007	0.009
Real Gross Wage	0.010	0.015
Investment	0.033	0.014
Household Income	0.013	0.015
Government deficit	-0.067	-0.085
Exports to the rest of the EU	-0.012	0.006
Exports to the rest of the world	-0.014	0.006
Energy use in UK households	0.015	0.008
Energy use in UK production sectors	-0.119	-0.121
Total energy use in the UK	-0.082	-0.085
Energy Productivity (GDP/energy use)	0.080	0.090
Share of household income spent on energy	0.002	-0.007
Economy-wide rebound	9.502	6.063

The source of the expansion is that the more energy efficient 'Road and Rail Transport' industry realises a decrease in the cost of production, which translates here to a decrease in the price of output. This boost to competitiveness flows forward via other UK industries that (directly or indirectly) use 'Road and Rail Transport' outputs in their own production.[6] The positive competitiveness effect is partly offset by rising labour and capital costs, though this eases into the long-run when capital stocks are able to adjust via investment.

[6] It is important to note that this is most likely largely due to the efficiency improvement occurring in both public and freight transport components of the UK sector.

Figure 1: Long-run changes in output and energy use in industries other than Road and Rail (% change from base)



In the long-run, 'Road and Rail Transport' is the main industrial beneficiary, with output rising by just under 7%, while energy use falls by 6.3% (not illustrated in Figure 1 for reasons of scale). Relative to the potential energy savings of 10%, this equates to a 37% general equilibrium rebound effect at the sectoral level (i.e. the sectoral effect is not limited to direct rebound, rather incorporating the full impacts of economy-wide adjustment). The economy-wide rebound effect reported in Table 1 reflects the share of total energy use actually affected by the efficiency improvement.[7] That it is proportionately smaller than the own-sector rebound, and bigger in the short-run (9.5%) than in the long-run (6%), reflects the presence of 'disinvestment' effects in the energy supply chain referred to by Turner (2009). Disinvestment occurs when falling returns to capital cause a contraction in capacity and put upward pressure on local energy prices in order to allow the capital market to adjust.

Let us focus now on our hypothesis that it may be possible to reduce economy-wide rebound effects without sacrificing macroeconomic benefits. We have argued that such an outcome may occur if the cost reducing properties of increased energy efficiency in public transport provision

[7] Economy-wide rebound is calculated as one plus the percentage change in total energy use divided by the percentage increase in energy efficiency (10%) times the share of total energy use affected by the efficiency improvement (i.e. base year energy use in 'Road and Rail Transport' divided by total base year energy use in the economy). In the long-run, for total energy use, this is 1+(-0.085/(10*0.009).

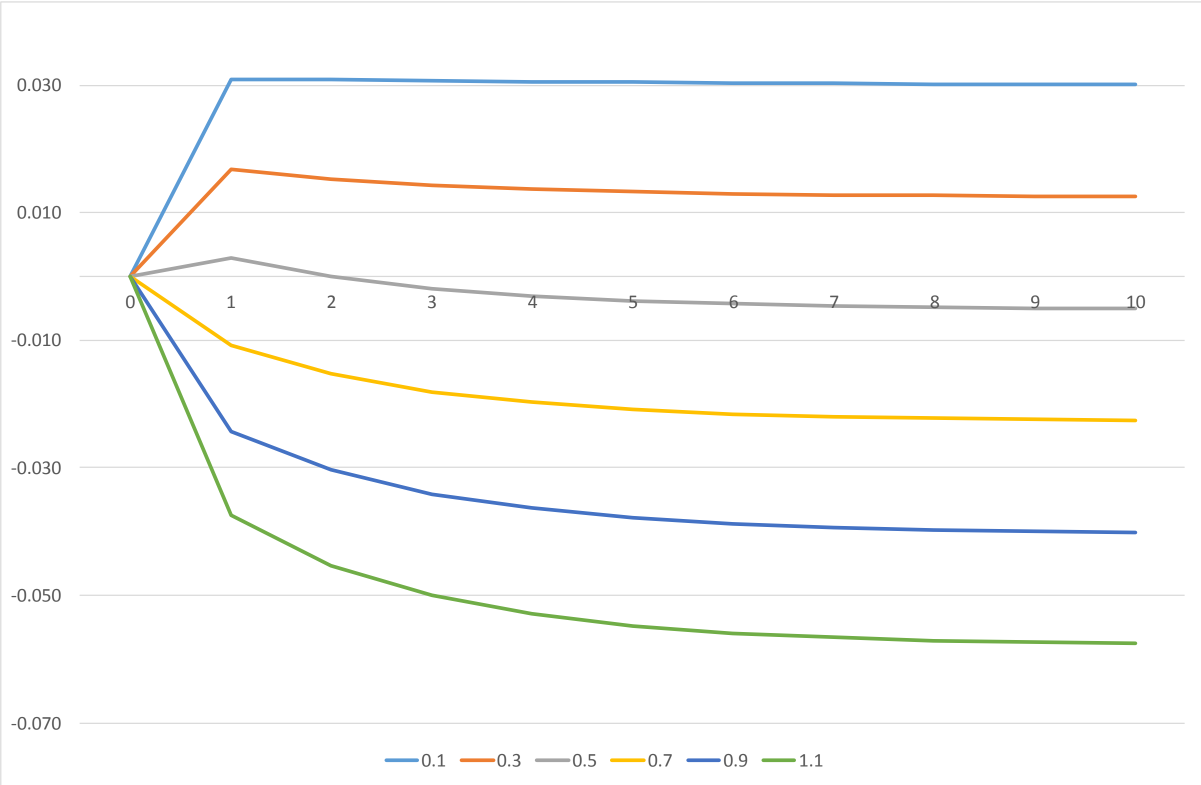
are utilised to make it a more attractive substitute for private means of delivering mobility/transport services. In the CGE model as specified here (see Appendix 1) the obvious means of doing this is if the reduced cost of production is passed on through a reduction in the relative price between public and private transport faced by UK households. The greater the price elasticity of substitution between public and private transport options in the household consumption decision, the more the *composition* of (what is, given the rise in income, a net increase) in household demand for transport will shift in favour of more energy efficient public transport over fuel-intensive private option.

To test this hypothesis for the case study presented here, we repeat our central simulation varying just one parameter. This is the elasticity on the household choice between private and public transport (which was set at 0.5 in the base case reported in Table 1). We test a range of discrete values for this elasticity: 0.1, 0.3, 0.5, 0.7, 0.9 and 1.1. We find that all macro-level non-energy variables (including but not limited to those reported in Table 1) and price variables (including energy prices) are not sensitive to changes in this parameter, including total household income and expenditure. However, the composition of household expenditure is sensitive, with the key impact being on household use of refined fuels and public transport options. We find that household demand for public transport rises at all elasticity levels, but at an increasing rate as we increase the price elasticity of substation.

However, the impact on refined fuel demand is a bit less straightforward in our results. Consider the case in Figure 2 where the elasticity of substitution between public and private transportation is set at its lowest value (0.1). Here, because of the increase in household income as the economy expands, combined with a slight decrease in the price of refined fuel as 'Road and Rail Transport' industry demand contracts with the efficiency increase, there is an increase in demand for refined fuel. That is, demand for both public and private transport increases when we set the substitution elasticity at this value. However, as the elasticity of substitution in households' choice between private and public transport increases, the upward pressure on demand for refined fuel lessens and ultimately declines from the outset as people choose to take the more competitive public transport.[8]

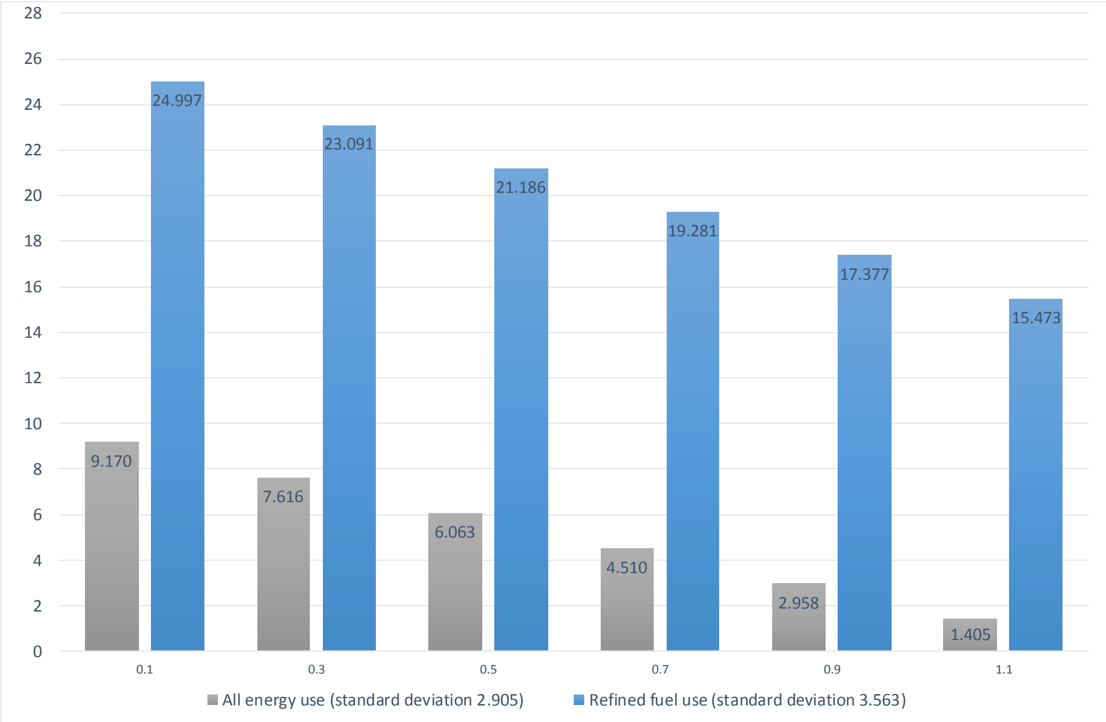
[8] In the specific results reported in Figure 2 there is a turning point in what is our central case, where the elasticity is equal to 0.5, with demand for refined fuel initially rising before dropping below base year level 2-3 years after the efficiency improvement in public transport occurs (as the constraint on capital in the latter falls permitting a greater drop in price). When we increase the elasticity to 0.7, demand for fuel (and the automobiles it is used in to 'produce' private transport) decreases from the first period.

Figure 2: Impact on UK Household use of refined fuels of varying elasticity of substitution between private and public/commercial transport in the household consumption choice (% change from base, by year)



This in turn impacts on economy-wide rebound in energy use both on the production side of the economy (mainly due to contraction in refined fuel supply activity) but even more so at the level of total (including final household consumption) use of energy. In Figure 3 we emphasise the key result of our illustrative analysis by separately identifying economy-wide rebound in refined fuel use. The decrease in total refined fuel use is proportionately greater than that in total energy use in all cases. This may be expected given the importance of refined fuel in the energy mix of commercial road and rail transportation. However, it is the variability of the impact on household use of refined fuel in personal transportation activity that it is the main cause of the sensitivity in the economy-wide rebound result for this type of energy use in Figure 3.

Figure 3: Impact on economy-wide rebound effects (%) of varying elasticity of substitution between private and public/commercial transport in the household consumption choice (0.5 central case)



Thus, the key message from this illustrative modelling exercise is that it is in principle possible to reduce economy-wide rebound, thereby increasing energy savings, without sacrificing the macroeconomic benefits of an energy efficiency improvement on the production side of the economy.

We have tested the sensitivity of this result to a greater extent of economic expansion by relaxing the assumption of a fixed national labour supply. This is done by introducing the possibility of migration from outside the UK (assumed to be from other EU member states) in response to the higher real wage and lower unemployment rate reported in Table 1 (Layard et al. 1991). The key impact is a reduction in the crowding out of non-energy supply sectors in Figure 1 and higher economy-wide rebound in total energy use. However, this result simply reflects greater economic expansion, with the long-run impact on the energy productivity indicator the same as is reported in Table 1. The core qualitative nature of the impacts on the household choice between public and private transport, and on the degree of sensitivity of both the refined fuel and all energy economy-wide rebound in Figure 3, is unchanged.

In terms of policy implications, the analysis suggests a key focus for attention may be to make public transport more energy efficient and more attractive as a substitute for personal transport.

We acknowledge that pricing, and how people actually pay for public transport, may be a more complex issue in practice than reflected in our modelling analysis above. Then the key issue may be whether cost savings from increased efficiency in public transport provision can somehow be used to increase the attractiveness of public transport options. This is an issue worthy of further investigation, including how transport demand is specified and introduced into multi-sector economy-wide CGE models. Nonetheless, it is likely that more micro-level transport modelling would also be required.

However, our intention here is to consider a more general possibility. It is our proposition that research is required to assess whether the type of result reported above would occur in a wider set of cases, particularly different options for delivering key energy services such as heating (which may involve household choice between low carbon delivery methods such electric rather than gas heating systems, or, moving more up-stream, in replacing gas networks with hydrogen ones). The wider question is whether energy efficiency can play a role in inducing substitutions between low and higher energy/carbon service options in serving a dematerialisation agenda aimed at shifting to more sustainable and/or low carbon development paths where changes in the *composition rather than level* of economic activity become a reality.

6. Conclusions: implications for policymakers and future research

Economy-wide rebound effects are generally symptomatic of increased economic activity triggered by increased energy efficiency. Here we have argued that, in a similar manner to any other policy, assessment of an energy efficiency policy should be considered from a societal welfare cost-benefit perspective. In this light, the realised energy savings are unlikely to be the only measure of success or otherwise of the policy, rather the economic impacts and increased societal welfare may be an equal or higher priority for many regional and national policymakers and members of the public.

We argue that a key question is not one of how to mitigate rebound. Rather it is one of whether rebound can be reduced without sacrificing the macroeconomic benefits that share the same trigger (the initial reduction in the relative price of energy services in the sector/activity where efficiency improves), while identifying and understanding the distributional implications (across different industries and households). Where there is a binding constraint underlying the need to reduce energy use (e.g. climate change commitments), taking a welfare-maximising perspective implies that this should be treated in a similar way to any other macro-level constraints (e.g. on government budget, balance of payments etc.).

Through consideration of the channels through which economy-wide rebound occurs, we conclude that the level of substitution in demand between different energy-using *service* options may be a key parameter in decoupling rebound and societal gains from energy efficiency. We consider the implications of targeting energy efficiency measures at the less energy and/or carbon-intensive service options (e.g. using public transport to travel for a particular journey). We hypothesise that this may improve their attractiveness in terms of price or other characteristics relative to more energy/carbon-intensive competitors (e.g. using a private car for the same journey), thereby decoupling the rebound from any economic expansion that may be triggered by improved efficiency.

There are several policy implications arising from our analysis. First, there should be more attention to identifying and considering service options that may be the target of energy (and possibly other) efficiency policies with a view to enhancing their competitiveness with higher energy/carbon alternatives. This involves a change away from a somewhat narrow focus in current policy thinking that prioritises efficiency improvements mainly in energy-intensive activities. In terms of the academic rebound debate, this requires a shift of attention from focussing mainly on inter-fuel and energy/non-energy substitution possibilities in favour of considering competing means of delivering energy and energy-using services and how users substitute between different options. This is also likely to require more attention to how energy and particularly durable/investment goods interact in both delivering different heating and transport services and in delivering efficiency improvements in these services and their underlying energy uses.

However, as discussed above, and already accepted as the case in considering causal mechanisms that deliver economy-wide and macroeconomic effects of energy efficiency measures, this issue will ultimately need to be considered on a case-by case basis. Initial research activity may involve theoretical analysis of the conditions under which more efficient and competitive low carbon energy service delivery is likely to translate to a decoupling of economic expansion and economy-wide rebound. That is, whether the results of the public vs private transport case illustrated here are generalizable or transferrable to other cases.

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References

ACEEE (2014), *How does Energy Efficiency Create Jobs?* American Council for an Energy Efficient Economy Fact Sheet, Washington DC.

ACEEE (2015), "Recognizing the Value of Energy Efficiency's Multiple Benefits", *Report IE1502*, Washington DC.

Allan, G., Hanley, N., McGregor, P., Swales, J.K., Turner, K., (2007). The impact of increased efficiency in the industrial use of energy: a computable general equilibrium analysis for the United Kingdom, *Energy Economics* 29: 779–798.

Anson, S. and K. Turner (2009). "Rebound and disinvestment effects in refined oil consumption and supply resulting from an increase in energy efficiency in the Scottish commercial transport sector", *Energy Policy* 37: 3608-3620.

Armington, P. (1969). "A theory of demand for products distinguished by place of production", *IMF Staff Papers*, 16, 157-178.

Borenstein, S. (2015). "A Microeconomic Framework for Evaluating Energy Efficiency rebound and Some Implications", *The Energy Journal*, 36:1: 1-22.

Broberg, T., C. Berg and E. Samakovlis (2015). "The economy-wide rebound effect from improved energy efficiency in Swedish industries – a general equilibrium analysis", *Energy Policy,* 83: 26–37.

Brookes, L (1978). Energy policy, the energy price fallacy and the role of nuclear energy in the UK, *Energy Policy* 6: 94-106.

Chan, N. and K.W. Gillingham (2015). "The Microeconomic Theory of the Rebound Effect and its Welfare Implications", *Journal of the Association of Environmental & Resource Economists* 2(1): 133-159.

Copenhagen Economics (2012). *Multiple Benefits of investing in energy-efficient renovation of buildings,* Report commissioned by Renovate Europe, Brussels.

Diefenbach *et al.* (2014). *Monitoring der KfW-Programme „Energieeffizient Sanieren" und „Energieeffizient Bauen" 2013*, KfW, Frankfurt.

European Commission (EC) (2011), *Commission Staff Working Paper Impact Assessment,* Accompanying the document Directive of the European Parliament and of the Council on energy efficiency and amending and subsequently repealing Directives 2004/8/EC and 2006/32/EC, SEC(2011) 779 final, Brussels, 22.6.2011.

Gerarden, T., R. Newell, and R. Stavins (2015a), *Addressing the Energy Efficiency Gap,* Harvard Environmental Economics Program, Cambridge, Mass.

Gerarden, T., R. Newell, R. Stavins, and R. Stowe (2015b) "An assessment of the energy-efficiency gap and its implications for climate-change policy", *NBER Working Paper No. 20905.*

Gillingham, K., D. Rapson, and G. Wagner (2014) "The Rebound Effect and Energy Efficiency Policy", *E2e Working Paper 013*.

Gillingham, K. and K. Palmer (2014) Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence, *Review of Environmental Economics and Policy* 8 (1): 1-17.

Greening, L. A., D. L., Greene, and C. Difiglio (2000). Energy Efficiency and Consumption – the Rebound Effect – a Survey, *Energy Policy*, 28 (6-7): 389-401.

Guerra, A. I. and F. Sancho (2010). Rethinking economy-wide rebound measure: an unbiased proposal, *Energy Policy* 38: 6684-6694.

Howarth, R. B. (1997). "Energy efficiency and economic growth", *Contemporary Economic Policy*, Vol. XV.

Howden-Chapman, P., N. Pierse, S. Nicholls, J Gillespie-Bennett, H Viggers, M. Cunningham, R. Phipps, M. Boulic, P. Fjällström, S. Free, R. Chapman, B. Lloyd, K. Wickens, D. Shields, M. Baker, C. Cunningham, A. Woodward, C. Bullen, J. Crane, (2009). "Effects of improved home heating on asthma in community dwelling children: randomised controlled trial", *British Medical Journal,* 337: 852-855, British Medical Association, London.

International Energy Agency (IEA) (2007), *Mind the Gap: Quantifying Principal-Agent Problems in Energy Efficiency*, OECD/IEA, Paris.

IEA (2011). *25 Energy Efficiency Policy Recommendations*, OECD/IEA, Paris. https://www.iea.org/publications/freepublications/publication/25-energy-efficiency-policy-recommendations---2011-update.html

IEA (2014). *Capturing the Multiple Benefits of Energy Efficiency*, OECD/IEA, Paris.

IEA (2015). *World Energy Outlook 2015*, OECD/IEA, Paris.

Jaffe, A.B, R.G. Newell and R.N. Stavins (2005). "A tale of two market failures: Technology and environmental policy", *Ecological Economics* 54(2-3): 164-174.

Janssen, R. and D. Staniaszek (2012), *How Many Jobs? A Survey of the Employment Effects of Investment in Energy Efficiency of Buildings*, The Energy Efficiency Industrial Forum.

Jenkins, J., T. Nordhaus and M. Shellenberger (2011). *Energy emergence: rebound and backfire as emergent phenomena.* Report by the Breakthrough Institute. Download at http://thebreakthrough.org/blog/Energy_Emergence.pdf.

Jevons, W.S. (1865). *The Coal Question: Can Britain Survive?* First published in 1865, re-published by Macmillan, London, UK, 1906.

Khazzoom, J.D. (1980). "Economic implications of mandated efficiency in standards for household appliances", *The Energy Journal* 1: 21-39

Kuckshinrichs, W., T. Kronenberg, and P. Hansen (2013), "Impact on public budgets of the KfW promotional programmes "Energy-efficient construction", "Energy-efficient refurbishment" and "Energy-efficient infrastructure" in 2011", *STE Research Report*, Forschungszentrum Juelick, commissioned by KfW Bankengruppe, Frankfurt.

Layard R., Nickell S., Jackman R., 1991. *Unemployment: Macroeconomic Performance and the Labour Market*. Oxford University Press, Oxford.

Lecca, P., McGregor, P. G., Swales, J. K., & Turner, K. (2014). "The added value from a general equilibrium analysis of increased efficiency in household energy use". *Ecological Economics*. 100: 51–62.

Lehr, U., Lutz, C., and M. Pehnt (2013), *Volkswirtschaftliche Effecte der Energiewende: Erneubare Energien und* Energieeffizienz, GWS und Ifeu, Osnabrueck und Heidelberg, Germany.

Liddell, C and Guiney, C (2014), "Living in a cold and damp home: frameworks for understanding impacts on mental well-being", *Public Health*, 26: 1-9.

Maxwell, D., P. Owen, L. McAndrew, K. Muehmel and A. Neubauer (2011). *Addressing the Rebound Effect*. Report by Global View Sustainability Services. Download at http://ec.europa.eu/environment/eussd/pdf/rebound_effect_report.pdf

Revkin, A. (2014), *Is There Room for Agreement on the Merits and Limits of Efficient Lighting*, New York Times, 21 October 2014. http://dotearth.blogs.nytimes.com/2014/10/21/is-there-room-for-agreement-on-the-merits-and-limts-of-efficient-lighting

Ryan, L., S. Moarif, E. Levina, and R. Baron (2011). "Energy Efficiency Policy and Carbon Pricing", *IEA Information Paper*, OECD/IEA, Paris. http://www.iea.org/publications/freepublications/publication/energy-efficiency-policy-and-carbon-pricing.html

Ryan, L. and N. Campbell (2012) Spreading the Net: the Multiple Benefits of Energy Efficiency, *IEA Insights Paper*, OECD/IEA, Paris. http://www.iea.org/publications/insights/insightpublications/spreading-the-net-the-multiple-benefits-of-energy-efficiency-improvements.html

Saunders, H. (2015). "Recent Evidence for Large Rebound: Elucidating the Drivers and their Implications for Climate Change Models", *The Energy Journal* 36(1): 23-48.

Saunders, H. (2014). "Is what we think of as ''rebound'' really just income effects in disguise?" *Energy Policy* 57: 308–317.

Small, K. and K. Van Dender (2007). "Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect", *The Energy Journal*, 28(1): 25-51.

Sorrell, S., E. O'Malley, J. Schleich and S. Scott (2004), *The Economics of Energy Efficiency: Barriers to Cost-effective Investment,* Edward Elgar, Cheltenham and Northampton.

Sorrell, S. (2007). The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. Report edited by S. Sorrell and produced by the UK Energy Research Centre. Download at: http://www.ukerc.ac.uk/Downloads/PDF/07/0710ReboundEffect

Sorrell, S., J. Dimitropoulos, and M. Sommerville (2009). "Empirical estimates of the direct rebound effect: A review", *Energy Policy* 27(4): 3115-3129.

Turner, K. (2009). "Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK Economy." Energy Economics 31: 648-666.

Turner, K. (2013). ""Rebound" Effects from Increased Energy Efficiency: A Time to Pause and Reflect", *The Energy Journal*, 34(4): 25-42.

UK House of Lords (2005). Science and technology – second report. Science and Technology Publications, 2nd report of session 2005-06.

UNEP (2014) Chapter 4, *The Emissions Gap Report 2014*, UNEP, Nairobi.

Van den Bergh, J.C.J.M. (2011). "Energy conservation more effective with rebound policy", *Environmental and Resource Economics* 48: 43-58.

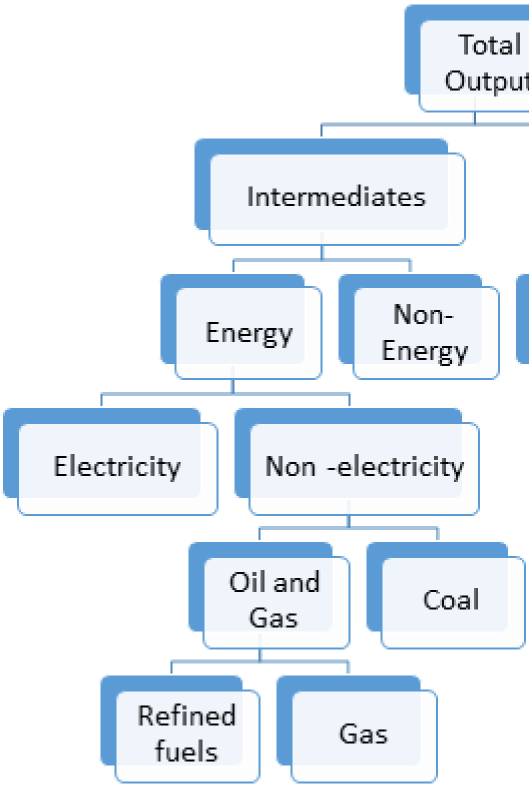
Whelan, R., T. Krebs, and T. Morgan (2015), *The Economic Impacts and Macroeconomic Benefitw of Energy Efficiency Programs in Oregon*, ECONorthwest, OR, USA.

Worrell, E., J. A. Laitner, M. Ruth, and H. Finman (2003). "Productivity benefits of industrialenergy efficiency measures", *Energy,* 28(11): 1081-1098.

Appendix 1. Overview of UKENVI CGE model specification

The version of our UK CGE model, UKENVI (Turner, 2009), used here is calibrated on a 2010 Social Accounting Matrix (SAM) for the UK. It includes 30 different production sectors, including energy industries supplying coal, gas, electricity and refined petroleum. The production function for each industry involves a KLEM nesting structure where energy (E) – a composite of imported and domestically produced electricity, gas, refined oil and coal - enters a CES nest alongside a composite of other produced inputs, or materials (M), which then combines with a capital-labour (KL) composite to produce output. The nested production function is illustrated in Figure A1. In our simulation exercise the efficiency improvement is introduced at the Energy nest in the Road and Rail Transport sector as a permanent step increase of 10% in (exogenous and costless) energy-augmenting technological progress.

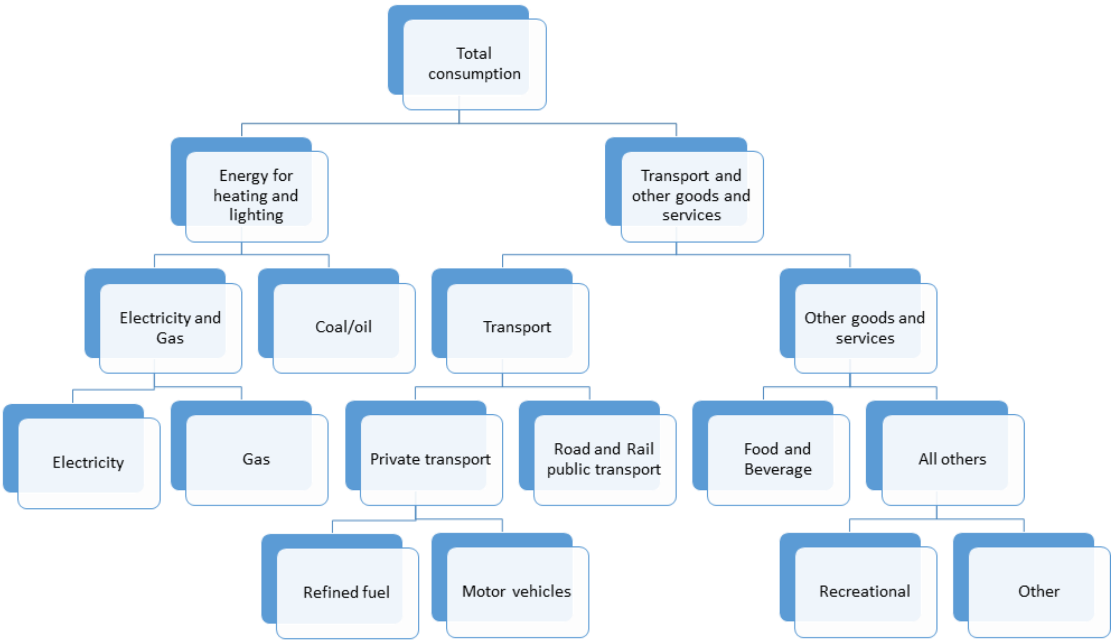
Figure A.1. Nested production function for each production sector in AMOSENVI



We identify final domestic public and private consumers (UK government and households), and income and trade flows with a single exogenous region, the rest of the World (ROW). UK and ROW products are imperfect substitutes (Armington, 1969) and export demands respond to changes in prices. Wages are determined in an imperfect competition setting, using a wage curve where the real wage is negatively related to unemployment rate. The total stock of labour is fixed at the national level (though, as discussed in the main text, we have relaxed this assumption to check whether our key finding is sensitive in the context of a fuller economic expansion). Investment responds to changes in the return to capital at the sectoral level, with a share of the gap between actual and desired capital stock filled in each period of adjustment. In the long-run capital stocks are fully adjusted to a new equilibrium level. A fuller description of UKENVI can be found in Turner (2009).

Here we focus attention on a key new element of model specification that has been introduced for the scenario analysed here. This is the inclusion of a transport nest within the household consumption decision, where public and private transport are substitutes in a CES nest, illustrated in Figure A.2.

Figure A.2. Nested household consumption function in AMOSENVI



Private transport involves a combination of refined fuel use and motor vehicles. We set the elasticity of substitution between private and public transport to 0.5 in our central case scenario, but then conduct sensitivity analysis of the results in response to varying the elasticity of substitution between public and private transport options (values between 0.1 and 1.1).

About the authors:

Lisa Ryan is Senior Power Systems Researcher at the Energy Institute, University College Dublin.
Karen Turner is Director of the Centre for Energy Policy (CEP), International Public Policy Institute (IPPI), University of Strathclyde.
Gioele Figus is a PhD student, Centre for Energy Policy (CEP), International Public Policy Institute (IPPI), University of Strathclyde.
Nina Campbell is a Senior Consultant at Databuild Research and Solutions Ltd.
Patrizio Lecca is a former member of staff in the Department of Economics, University of Strathclyde.
Peter McGregor is Emeritus Professor of Economics at the University of Strathclyde.
Kim Swales is Emeritus Professor of Economics at the University of Strathclyde.

Contact details:

Lisa Ryan
e: lisa.ryan@ucd.ie

Karen Turner
e: karen.turner@strath.ac.uk

International Public Policy Institute (IPPI)
McCance Building, Room 4.26
University of Strathclyde
16 Richmond Street
Glasgow G1 1XQ

t: +44 (0) 141 548 3865
e: ippi-info@strath.ac.uk

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