‘Rebound’ effects from increased energy efficiency: a time to pause and reflect

By

Karen Turner

Division of Economics, Stirling Management School, Cottrell Building,

University of Stirling, FK9 4LA, Scotland, UK. Email:

karen.turner@stir.ac.uk

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Abstract

The phenomenon of rebound effects has sparked considerable academic, policy and press debate over the effectiveness of energy efficiency policy in recent years. There has been a huge surge in empirical studies claiming rebound effects of hugely varying magnitudes. The contention of this paper is that the lack of consensus in the literature is grounded in a rush to empirical estimation in the absence of solid analytical foundations. Focus on measuring a single 'rebound' measure has led to a neglect of detail on precisely what type of change in energy use is considered in any one study and on the range of mechanisms governing the economy-wide response. This paper attempts to bring a reflective pause to the development of the rebound literature, with a view to identifying the key issues that policymakers need to understand and analysts need to focus their attention on.

Key words:

Energy efficiency; rebound; energy demand; energy supply

JEL classifications:

Q01, Q40, Q41, Q43

1. Introduction

The issue of whether rebound effects in energy use may partially or even wholly offset anticipated energy savings from increases in energy efficiency has become a source of considerable concern and debate in both academic and policy circles. While the academic literature on rebound has been growing over the last twenty to thirty years (triggered by the contributions of Brookes, 1978, and Khazzoom, 1980, building on much earlier foundations laid by Jevons, 1865) it is only in the last couple of years that the debate seems to have exploded. This has perhaps been triggered by policy attention to the potential implications of rebound. In 2005 the UK House of Lords published a report questioning whether rebound may provide an explanation as to why macro-level energy use and the energy intensity of UK GDP has not fallen as may be expected in the wake of efforts to increase energy efficiency throughout the economy. In response to this, and following advisory stakeholder input, the UK Energy Research Centre (UKERC) instigated and conducted a study reviewing and synthesising evidence on the rebound phenomenon. This is the well-known Sorrell (2007) report. Following this the interest of the European Commission was also sparked and it commissioned another evidence review by Maxwell et al. (2011). In the same year the Jenkins et al. (2011) or Breakthrough Institute review was also published. Given the policy interest in these evidence reviews, and the demands of the policy community for models that would permit empirical estimation of the importance of rebound in considering the effectiveness of future energy efficiency policies, there has been a surge in studies considering and/or measuring various aspects of rebound effects. Since 2007 (the year of the afore-mentioned Sorrell report), there have been 80 articles addressing this issue across six leading energy/environmental journals[1]: *Ecological Economics* (10 articles, e.g. Holm and Englund, 2009), *Energy* (6 articles, e.g. Ouyang et al., 2010), *Energy Economics* (15 articles, e.g. most

[1] Count made through Scopus search (conducted on 20 August 2012) of articles in press or published in these six journals with word "rebound" in their title, abstract and/or keywords.

recently Wang et al., 2012), *Energy Efficiency* (7 articles, e.g. Nässén and Holmbert, 2009), *The Energy Journal* (2 articles – Frondel et al., 2008, and Small and Van Dender) and *Energy Policy* (40 articles, most recently published Li and Zhang, 2012, and most cited Sorrell et al. 2009).

However, the contention of this paper is that empirical rebound research has run ahead of the required theoretical and analytical underpinnings. The more new papers that are produced, the more confusing and lacking in resolution the literature seems to be in explaining the sources and mechanisms governing rebound, and even what 'the rebound effect' is. Frustrating for an academic, the confusion and lack of clarity may have worrying impacts in terms of public and policy attitudes to energy efficiency improvements – see for example The Economist magazine's response to a paper by Tsao et al. (2010) on solid-state lighting, which draws the conclusion that old fashioned, energy inefficient light bulbs should be made compulsory.[2]

Therefore, the purpose of this paper is to urge rebound researchers to pause for thought. It identifies four major issues with the rebound literature that need to be investigated and clarified as a matter of urgency if rebound research is to play a useful, and not a counter-productive role in future energy and climate policy around the world. These are identified as: (i) problems with the current rebound taxonomies/typologies that new researchers and the policy community alike latch onto in trying to define the problem (Section 2); (ii) a lack of distinction between the very different mechanisms governing economy-wide responses to energy efficiency improvements in consumption and production activities respectively (Section 3); (iii) a lack of attention to and clarity in dealing with factors that put downward pressure on rebound (Section 4); and (iv) a lack of consensus on what is meant and understood by energy efficiency and how it is introduced to analytical models (Section 5). Conclusions are offered in Section 6.

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[2] The Economist, "Not such a bright idea", August 6, 2010. At http://www.economist.com/node/16886228.

2. The problem of classifying rebound effects

2.1 The first rebound classification – Greening et al. (2000)

In the earliest comprehensive review paper on the rebound phenomenon, Greening et al. (2000) identify a four-part typology/taxonomy of rebound effects: (1) direct; (2) secondary energy use; (3) market clearing price and quantity adjustments; (4) transformational effects. In referring to direct rebound they focus on the micro-level impact of the response to the reduced price of energy services, where the supply of these services increases when efficiency improves in the use of a physical energy input. Note that they later refer to this as an *effective price* change per *physical* unit of energy, which is akin to the *implicit price* change referred to in Jevons's (1865) and Brookes's (2000) arguments, but with this seemingly being regarded as a source of confusion by some later writers, such as Sorrell (2009). An equivalent alternative is to express in terms of the resulting impact on the derived unit price of the energy service in question.

Greening et al. (2000) then identify several types of secondary effects. First, they consider consumers and focus on increased demand for other (non-energy) goods and services, and the indirect energy requirements of their production, as direct expenditure on energy is reduced as a result of the efficiency improvement. However, they consider that these demand effects are likely to be insignificant where energy is a minor share of consumer expenditure. More recent research (e.g. Druckman et al., 2011) has challenged this conclusion, a point that we return to below. First a more fundamental issue must be considered.

2.2 Efficiency in industrial vs. household energy use

In considering their 'secondary' rebound effects, Greening et al. (2000) make one very important distinction that seems to have become conflated in later contributions. They note (p. 391) that "[*f*]*or firms* in a given sector, secondary effects result from (1) the increased demand for non-fuel inputs to their production process as a result of increased demand for output, and (2) the effect of the lower cost of one sector's output on production costs of other sectors" (emphasis mine).

The key distinction is with respect to (2). Here Greening et al. are referring to a key trigger for the productivity-led growth that is central to the Jevons's (1865) thesis underlying what has come to be known as the backfire (rebound greater than 100%) argument that is developed by Brookes (1990, 2000), Saunders (1990, 2000) and others, with more recent survey contributions focussing on this particular issue by Alcott (2005), Dimitropoulos (2007), Sorrell (2009) and Madlener and Alcott (2009). The crucial point, one that seems to have become lost in later works, is the demarcation that secondary effects resulting from *reduced* input costs and output prices will only occur if the efficiency improvement directly impacts the costs of production in *firms*. That is, it will only happen if a firm's own efficiency improves so that efficiency improves in energy use in *production*, not in household consumption (unless the price of labour supplied by households is impacted). We return to this point in Section 3.

2.3 The importance of supply as well as demand responses

Greening et al. (2000, p. 391) then identify (3) "price and quantity readjustments or economy-wide effects of both direct and secondary responses to technology-induced changes in the effective price per unit of fuel". In a footnote they clarify that this involves consideration of economy-wide rebound effects that take into account the interrelationship of prices and outputs of goods and resources in different markets. Crucially, in both the text and footnote, they note that adjustment to a new macroeconomic equilibrium will involve supply as well as demand-side responses to changing prices and quantities. In particular, they note that adjustment in *fuel* *supply* markets may be significant. Greening et al. do not explore this issue, with their empirical review going on to focus solely on direct rebound effects, and they only cite one other work in this area, a policy paper by Kydes (1997). It is the contention of the current paper that the issue of supply-side effects in general, and energy supply responses in particular has since been neglected in the rebound literature (though with some more important recent exceptions through general equilibrium studies – for example, Turner, 2009, and Wei, 2010 - and an early, but much overlooked, contribution by Zein-Elabdin, 1997, highlighting the role of supply as well as demand elasticities). This has led to a neglect particularly of potential constraining, or even negating, impacts on rebound, a possibility highlighted by Turner (2009), and one that we return to below.

2.5 Do we now have a clear classification of 'rebound' effects?

Van den Bergh (2011) argues that the Greening et al. (2000) taxonomy is not entirely satisfactory due to crossover between the different categories, particularly with respect to economy-wide rebound effects, which may impact each and all of them.[3] He contrasts the Greening et al. taxonomy with Sorrell's (2007) simpler categorisation of direct and indirect summing to economy-wide rebound effects. However, the simplicity of Sorrell's typology means that it tends to be interpreted from the perspective of additive demand effects as the boundaries of rebound effects considered increase. In contrast, Greening et al.'s (2000) typology – which also includes a fourth category of 'transformational effects' where consumer preferences (the argument could also apply to producers) for existing or new products (inputs) are impacted by efficiency improvements - may be argued to have more in common with Van den Bergh's own approach, where he provides a more comprehensive list of

[3] The decomposition of different types of rebound effect is problematic, particularly empirically. For example, even direct rebound calculations may be distorted by observing energy use data as a given energy user's use of a particular fuel may rise as efficiency increases both because of the decrease in effective price of that fuel but also because of a wider set of income effects as economy-wide adjustment takes place. Moreover, different elements of rebound effect will be interdependent: for example, the strength of the direct rebound effect will impact negatively impact on the size of re-spending effects (the more energy is saved the greater will be the freed up income available to spend on other goods and services).

potential rebound mechanisms than previously presented in the literature. Similarly, Sorrell (2009) later goes on to distinguish five different types of effects that fall under his indirect classification: an embodied energy effect[4], re-spending effects, output effects (which are inherently focussed on the case of increased energy efficiency in production), energy market effects and composition effects (again inherently focussed on the production case – see below). The key difference is that Van den Bergh (2011) does not attempt to squeeze these into a typology, rather focussing on clearly identifying a range of mechanisms that should ideally be considered but may or may not be captured by different analytical approaches.

Thus, one contention of this paper is that identification of a rebound typology/taxonomy, while pedagogically useful, if attempted too early may lead to confusion and neglect of potentially important mechanisms influencing the nature and magnitude of the economy-wide (national and global) response to increased energy efficiency. This is reflected in the fact that reviewers such as Sorrell (2009) and Madlener and Alcott (2009), while presenting in this manner, seem to also find it limiting. Both talk about the need to expand the boundaries of economy-wide rebound, particularly to take international impacts into account, an issue also raised by Van den Bergh (2011). Generally, the issue of the spatial boundaries within which rebound effects are considered and estimated has not been given sufficient attention in the rebound literature to date. Particularly if the energy use (and associated pollution generation) impacts of increased energy efficiency are considered in the context of global energy security and climate change, there is a need to consider the impacts of changes in behaviour in any one locality on energy demand and supply at a global level through changes in import and export activity.

[4] We return to the definition of 'embodied' energy effects below. Sorrell's (2009) definition relates more to the energy requirements of capital goods required to bring about an efficiency improvement (an *ex ante* change) rather than the consideration of changes in energy embodied in any and all goods and services where expenditure may be directed or redirected *ex post*. The latter may falls more clearly under Sorrell's (2009) 're-spending' effect. See Section 4 below.

Saunders and Tsao (2012) also raise the issue of wider ‘frontier’ effects, where efficiency gains in particular energy services (they consider lighting) create opportunities for new products, applications and possibly industries. Van den Bergh also identifies the potential for such effects but refers to them as ‘technological innovation and diffusion effects’ (both contrast with Greening et al.’s transformational effects identified above, which do not require new products). Thus, there is a need to clarify and explore these mechanisms also and the spatial element is likely to again be important in a modern global economy.

Moreover, outside of the macro-focussed analyses of writers like Brookes and Saunders, there has been little attention to the issues of temporal boundaries on rebound. As economies adjust to changes in efficiency at the micro-level, the size and nature of rebound effects are also likely to change, with pressure for either expansion or contraction. As we discuss in more detail below, Turner (2009) has shown that energy supply responses will be a key determinant in this respect. At this point, a central contention of this paper is that the lack of attention to energy supply issues in the rebound literature is a fundamental source of concern. Again, in considering their rebound taxonomy, Madlener and Alcott (2009) in particular seem to struggle with how to consider potential supply-side effects as they mention the need to take account of global energy markets (an issue raised earlier in the literature by Birol and Keppler, 2000). However, outside of their own taxonomy, Madlener and Alcott do not develop this even to the extent of Greening et al. (2000), who, as noted above, mention (but do not explore) the need to consider price and quantity adjustments in energy supply markets.

Generally, and particularly in the case of ‘economy-wide’ rebound effects (as noted by Dimitropoulos in his 2007 review), we still lack a rigorous theoretical framework to explain the mechanisms and consequences of rebound effects at the macro level. Therefore, it would seem more prudent to follow the Van den Bergh (2011) approach of working to identify and consider a range of potentially important determinants of the economy-wide response to increased energy efficiency in any one activity. However, this should be done without focussing on closing the debate on a prematurely agreed typology of 'rebound' that researchers should work within/link their findings to. More fundamentally, caution should perhaps also be exerted in trying to squeeze a very wide range of possible responses to energy efficiency improvements into a single measure of 'rebound'.

3. Energy efficiency improvements in final consumption vs production

3.1 Households vs. firms

Section 2.2 identified a crucial issue in terms of distinguishing between the impacts of energy efficiency improvements made in final consumption activities (particularly in the household sector in household heating/cooling/lighting and personal transportation) and in production (through agricultural, commercial, industrial, public sector and freight transportation activities). A key point is that Jevons (1865) focussed on energy and other inputs to *production*. He (p.138) actually explicitly states "I speak not here of the *domestic* consumption of coal" (emphasis mine). As Van den Bergh (2011) points out, the basic energy saving strategies that constitute energy efficiency improvements may be similar for households and firms, as may be the mechanics of basic partial equilibrium analysis of direct rebound (though this may be disputed particularly given different concerns regarding multiple inputs, cost minimisation vs. utility maximisation etc.). However, the key issue explored in this section is that the transmission mechanisms determining the wider rebound effect are likely to be very different.

As noted above, Greening et al. (2000) consider energy efficiency by both consumers and firms, making a distinction between the two broad cases. In the same special issue of *Energy Policy*, Berkhout et al. (2000) also make a very clear distinction, offering basic partial equilibrium micro analysis for the production and consumption cases in turn, but do not extend beyond this level of analysis. Birol and Keppler (2000) focus entirely on the production case. However, later writings, particularly in the widely read 'rebound review' studies cited in the introduction to this paper, often focus on the consumption case (household energy efficiency) in considering direct rebound but then go on to discuss the production case in considering economy-wide rebound effects. This may be due to the dominance of household studies in the case of direct rebound and industrial studies in the case of the much smaller empirical literature on economy-wide rebound. However, there would seem fundamental issues with the definition and interpretation of the theoretical basis for rebound in the two cases.

3.2 'Production' of 'energy services'

One possible explanation for the confusion and conflation of the impacts of energy efficiency improvements taking place in (final) consumption activities relative to production may stem from the concept of all energy users using energy (along with other 'inputs') to 'produce' energy services. Khazzoom's seminal (1980) analysis of the efficiency of appliances is inherently consumption focussed but he talks about *supply* of energy services, as do Greening et al. (2000), while Sorrell and Dimitropoulos (2007) use Becker's (1965) 'household production' model. The distinction may be a useful one but the nature of 'supply' or 'production' of energy services must be carefully interpreted.

One issue is that energy services are not directly marketed commodities and their prices are a derived rather than market ones. This raises issues in terms of identifying price elasticities as data do not tend to be reported on the former. However, a more fundamental point is that this is not production activity in the conventional sense that underlies GDP measurement (where household production in general is not included) or the position of the production possibility frontier. The manner in which households contribute to this production is in the supply of labour services (and capital, where they are owners/recipients of returns). Thus, unless increased efficiency in their use of energy leads to households being willing to supply labour (and/or capital where relevant) at a lower real wage rate this will *not* trigger a process of productivity-led growth. Rather, any economic growth will come through shifts in demand that are akin to a simple change in tastes, but with an increase in real income provided by the reduction in implicit price of energy or the price of energy services. This is a crucial difference: in the absence of increased productivity and/or expansion in supply-conditions, increased household demand will stimulate production to meet higher demand putting *upward* rather than downward pressure on factor and output prices, thereby *reducing* competitiveness, with domestic consumption potentially 'crowding out' export demands. The net impact on economic activity and energy use will depend on the specific case being analysed. However, the key issue is the difference in the nature of the adjustment mechanism relative to cases where efficiency improves in production, where both productivity and competitiveness increase, permitting expansion in both domestic and external demands.

Further emphasising the importance of household labour supply decisions, Madlener and Alcott (2009) identify a category of 'rebound demand' (again emphasising the demand focus of more recent rebound typologies) as arising from consumers' choice between leisure and additional consumption. Madlener and Alcott (2009) focus on how this may lead to zero rebound if additional leisure time has no embodied energy use or macroeconomic impacts (such an argument may also apply to the choice between present consumption and saving). Greening et al. (2000) also raise the time allocation issue, but they do so in the context of labour market participation rates and occupational structure. However, there may be a more straightforward transmission mechanism if additional leisure time involves a decrease in labour supply as this may (depending on labour market conditions) raise nominal and real wage rates (the price of labour) and negatively impact production possibilities. This author's judgement is that the issue discussed in the previous paragraph regarding the direct real wage impacts of increased efficiency in household energy use is a more immediate concern in understanding economy-wide impacts. However, the general point here is the need to consider the nature of transmission mechanisms from changes in household consumption activity to the supply (production) side of the economy.

3.3 The need for more work on theoretical foundations and empirical case studies

In short, the lack of attention to differences in the nature of economy-wide response mechanisms that are likely to apply whether energy efficiency improvements take place in production or final consumption is a fundamental problem with the rebound literature to date. Perhaps it is one that has not been picked up because there have been no published studies attempting to lay analytical or theoretical foundations to understand the causal processes underlying the wider macroeconomic response to increased energy efficiency in final consumption. As far as is known, the only applied general equilibrium study focussing on an efficiency increase in household energy use is Dufournaud et al. (1994), but this focuses very specifically on wood-burning stoves in the Sudan, a case that is difficult to generalise. As a result, while direct rebound analyses have focussed particularly on increased efficiency in household energy use, contributors to the literature seem to draw on the limited empirical findings from studies of macro rebound effects from increased efficiency in *production* in widening focus to economy-wide rebound effects. However, the relatively small set of general equilibrium and non-equilibrium economy-wide studies (reviewed in Sorrell, 2007, with more recent rebound focussed case studies including Anson and Turner, 2009;

Barker, 2007; Barker et al., 2009; Turner and Hanley, 2011; Wei, 2010), while putting forward some important insights on different mechanisms underlying macro-level rebound effects, have not yet established a solid theoretical foundation on the production side either.

4. Embodied energy effects and downward pressure on 'rebound'

An interesting area of rebound research has recently developed in considering the embodied energy effects of the re-spending decisions that households make when they realise savings from reduced expenditure on energy as efficiency increases. These may be considered using the simplest general equilibrium framework, input-output (IO) models, where changes in quantities are considered abstracting from any price effects. At this point it is important to note that demand-driven quantity IO models are not ideal for modelling the impacts of increased energy efficiency, particularly if efficiency improvements take place in production, which constitutes a change in supply conditions. Moreover, they cannot deal with the impacts of changes in prices. Generally the production side of demand-driven IO models is rigid. Similarly, supply- or price- driven IO models may be used to emulate producer behaviour in response to efficiency changes, but treat the consumption side as rigid. For this reason, more flexible applied or computable general equilibrium, CGE, models (which incorporate IO accounts in their database and capture the same inter-sectoral linkages) are more suitable for considering economy-wide rebound effects. The Turner (2009) analysis discussed below adopts a CGE approach to consider rebound in a broader economy-wide setting. Nonetheless, IO models are useful to isolate embodied energy effects of changes in final or intermediate demand patterns that may result from energy efficiency improvements.

Specifically, IO multiplier analysis is ideal for examining energy and/or pollution embodied throughout industrial supply-chains (see Turner *et al.*, 2007, for the IO multiplier method which is also commonly employed in environmental 'footprint' studies). Two examples are found in Druckman et al. (2011) and Freire-Gonzàles (2011) for UK and Spanish (Catalonia) case studies respectively, where indirect energy use embodied in re-spending decisions is found to be large in a number of scenarios modelled. However, in considering IO multiplier results it is crucial to identify that as well as *increased* embodied energy requirements of the consumption goods that households may reallocate their expenditure in favour of, there will also be *reduced* embodied energy requirements from energy-savings (inputs and outputs of the energy supply sectors in the IO model) where rebound is less than 100%. That is, all goods and services have an embodied energy requirement through direct energy use in their production and indirect energy use embodied in the intermediate inputs used in their production. Thus, just as increased consumption of non-energy goods and services involves increased embodied energy requirements down their supply chains (positive multiplier effects), reduced consumption of energy involves decreased embodied energy requirements as less energy and non-energy inputs are required in the supply chains of energy producers (negative multiplier effects). Moreover, energy production (for example, electricity generation in gas- or coal-fired plants) tends to be both directly and indirectly energy-intensive. Thus, there is a strong chance that redirected spending away from the energy-intensive outputs of energy supply sectors in favour of less (directly and indirectly) energy-intensive non-energy goods and service will lead to a net *negative* embodied energy effect. This will be captured by IO models as long as a full set of expenditure changes (both positive and negative) are introduced.

Turner (2009) considers this issue for the case of energy efficiency in production in a computable general equilibrium (CGE) modelling context. Here findings of net *negative economy-wide rebound* occur as a result of the reduced intermediate energy input requirement of Scottish production sectors where efficiency increases in industrial energy use. Reduction in the direct intermediate use of energy sector outputs is the engineering saving; however, there are also negative impacts on indirect energy use embodied in energy sector outputs (e.g. reduction in intermediate use of coal or gas by the electricity supply sector when efficiency in industrial use of electricity increases). The latter constitute negative multiplier effects in energy sector supply chains that act to offset reductions in the 'actual energy savings' (AES) that constitute the numerator in the standard rebound calculation (where PES is the 'potential energy savings' that may be associated with the expected engineering savings):

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

However, this finding is implicitly disputed in a paper by Guerra and Sancho (2010). They argue that negative multiplier effects in the energy supply chain (reductions direct and indirect use of energy by energy producers through their intermediate use of both energy and non-energy inputs) should be incorporated into the 'potential energy savings' that constitutes the denominator of the standard rebound calculation above. If not, they argue that there will be downward bias on economy wide rebound estimates. Thus the Turner vs. Guerra and Sancho argument centres on whether the 'potential energy saving' in the denominator of [1] should be limited to the anticipated or engineering savings that equate to the size of the efficiency improvement or include indirect energy supply chain effects. This author's contention is that, since indirect energy savings will not be known ex ante (unless policy analysts have access to appropriate IO models), practical considerations and the understanding of policymakers should overrule the strict general equilibrium conditions that Guerra and Sancho (2010) introduce. Again, one becomes concerned that definition and measurement of a single 'rebound' measure has begun to override understanding of the range of economy-wide responses that may occur and the fact that different mechanisms may exert upward or downward pressure on macro-level energy use.

In the Turner (2009) paper, this author identifies another source of downward pressure on economy-wide rebound (but this time a price driven one that cannot be considered in a fixed price IO framework). It again relates to the response of energy suppliers to the excess capacity experienced in response to initial energy savings when efficiency (in production or final consumption) increases. In the short-run, energy suppliers may respond to excess capacity by reducing their output price. This will provide further impetus for rebound. However, over time, if the subsequent demand response is not sufficiently elastic to prevent revenues earned by energy suppliers from falling, this may result in a contraction in capacity or a 'disinvestment' effect that will lead to a tightening of energy supply conditions and reverse pressure on energy prices. This will cause economy-wide rebound to decrease in size as the economy adjusts to a new equilibrium. Turner (2009) explains that this finding, which contradicts the theoretical predictions of Wei (2007) and Saunders (2008) that economy-wide rebound will be larger in the long-run than in the short-run, is driven by one key variable: the treatment of the return on capital, assumed to be fixed in the models of Wei and Saunders but endogenous (and responding to profitability) in Turner's model.

The Turner (2009) findings require further investigation, particularly in the context of imperfectly competitive energy supply conditions where price setting behaviour (albeit often in a regulated context) will introduce an additional layer of complexity. However, once again the importance of considering the supply-side of the economy in general and energy supply conditions in particular is emphasised as a priority topic for future research.

5. Considering the nature of energy efficiency improvements

However, there is another very fundamental area in which the existing rebound literature is less than clear. This is in terms of what different studies actually mean by energy efficiency improvements and how they are introduced. One particularly problematic issue is the treatment of capital costs involved in making efficiency improvements.

5.1 Capital costs involved in introducing energy efficiency improvements

Greening et al. (2000) raise the issue of capital costs, which has remained a source of debate in the rebound literature, but is yet to be effectively resolved. In doing so they distinguish between (1) potential technological efficiency improvements (the efficiency improvement that could occur) and (2) realised or actual efficiency improvements (what is actually implemented). They explain that most rebound estimates are based on (2) rather than (1) and they attribute the decision of what is actually implemented to explicit consideration of the initial cost of energy using capital. This would seem to suggest that capital costs do not impact on rebound effects as such, rather on the size of the efficiency improvement modelled. However, Greening et al. then go onto distinguish between short and long run decision-making with consideration of capital costs impacting in the long-run.

Similarly, Sorrell & Dimitropoulos (2007) argue that higher capital costs may lead to uptake of fewer/smaller and/or different conversion devices. However, again, it is not clear whether and how this will affect the size of rebound in physical energy use in response to a given energy efficiency improvement that has occurred. Rather, it may simply relate to the uptake of technology. Sorrell and Dimitropoulos also talk about 'rational' consumers, who the capital cost argument doesn't apply to (on the basis that utilisation doesn't depend on sunk investment costs), set against what seem to be uptake/inertia problems (also raised by Greening et al., 2000, and considered in more depth by other writers such as Sorrell et al., 2004). However, it may be argued that the latter could be captured through differences in short and long run price elasticities for the physical energy demand in question and/or the incorporation of non-economic factors (perhaps drawing on the input of other social science disciplines such as psychology) in specifying models.

A key point would seem to be that capital costs are fixed costs while the marginal energy and service use decisions underlying rebound are based on variable costs. Given that capital and other investment costs are sunk prior to an efficiency improvement being made, the rational consumer may look to maximise the benefit gained by investment and installation by *increasing* physical energy use and/or use of the energy service as unit costs fall. Even if investment has involved financing that requires the user to make repayments over time, this would seem to be more of an income constraint question than one of price responsiveness. It would seem to be recognition of this type of reasoning that leads Alcott (2005) to explicitly ignore capital costs.

The key issue in the debate seems to be whether the initial direct rebound is estimated in terms of physical energy use or energy services. Since the former involves considering market rather than derived prices, it may seem more straightforward empirically. However, there is a need to focus on the subset of uses of a given physical energy use where efficiency has improved – for example, electricity used to run a refrigerator. This implies a need to shift towards considering the own price elasticity for a given energy service. Henly et al. (1988) – the most commonly cited paper in the capital cost debate – argues that capital costs involved in improving efficiency will impact on this price response, and that the impact will vary across different time periods. They provide a critique of Khazzoom's (1980) theoretical formulation of rebound, which assumes away the costs of new appliances (capital costs in a consumer-focussed analyses). Henly et al.'s formulation (later applied more recently by Mizobuchi, 2008) builds investment costs (the price of an appliance as a capital or durable good) into the *long-run* own price elasticity of *energy service* demand which (set against reduced operating costs of a more efficient appliance) they argue reduces direct rebound.

This issue of requires fuller consideration in the literature, if nothing else to define the terms of the problem that we are attempting to address. It would seem sensible to carefully consider the different stages of the efficiency improving process for different practical examples (in both household final consumption and production). This would involve giving particular attention to the question of just what type of efficiency improvement is made, whether, for example, any R&D costs are involved in identification of efficiency improvements (e.g. see Fisher and Vanden-Ho, 2010), then how and when capital costs come into decision making processes (and also any post-installation operating and maintenance costs associated with capital equipment/durable goods).

5.2. What do we mean by energy efficiency?

Van den Bergh (2011) also raises a fundamental issue in terms of whether economic understanding of energy use and efficiency is sufficient to properly identify and understand the problem. He calls for more attention to the work of Ayres and colleagues (e.g. Ayres et al., 2003) in considering the nature of physical energy use. Much earlier in the rebound debate, Birol and Keppler (2000) made the point that engineers and economists may have different views in terms of constraints on the range of technologies and substitution possibilities available to facilitate energy efficiency improvements. Useful insight from an engineering perspective is provided by Sorrell (2009). Following Patterson (1996), he defines energy efficiency by thermodynamic, physical and economic measures, noting that the rebound debate to date has focussed on the latter, where emphasis is on energy productivity with outputs from energy use measured in economic terms (real value of output). Ruzzenenti and Basosi (2008a) focus on the thermodynamic nature of energy efficiency and Lotka's (1956) definition of an efficiency-power (effectiveness and speed respectively with which energy is processed) trade-off. The basic implication of this trade-off for the rebound debate is that increased efficiency can shift the power output of machinery, thereby widening the gap between potential and actual energy savings independent of the economic drivers of rebound. The same authors offer a second analysis that provides “an evolutionary perspective” (Ruzzenenti and Basosi, 2008b, p. 526) on rebound where they propose a link between the complexity of the global economic and biological systems and the declining impact of efficiency improvements as global energy demand increases and particularly traffic density grows.

Different definitions of energy efficiency will be appropriate in different circumstances. However, there is a problem in that it is often not clear what different authors mean by energy efficiency (a point also highlighted by Dimitropoulos, 2007, and Sorrell, 2009) and/or whether they focus on technological change that leads to a change in the price of an energy service as the rebound trigger. In this respect, some studies (e.g. Druckman et al. 2011) consider ‘rebound’ in energy use from behavioural changes that do not actually involve any technological change to reduce the physical energy used to ‘produce’ an energy service (and thus with no reduction in the price of that service), rather decisions to reduce the use of a given energy service. Van den Bergh (2012, p.534) also extends the context where rebound may apply to conservation as well as efficiency improvements as “relieving a limit on a scarce resource”, and thus impacting the price of that resource. Alcott (2008) further extends by considering rebound effects of sufficiency or frugality strategies that put downward pressure on energy (and other resource) prices, which may stimulate demand elsewhere in the economy.

6. Conclusions

Generally, then, a starting point in bringing some clarity to the rebound debate must be to develop a consensus on (a) what we mean (and understand) by ‘energy efficiency’, (b) how it triggers rebound (including what, if any, impact capital costs have on this trigger), and (c) whether any other energy-saving strategy, such as voluntary or enforced conservation/behavioural change will trigger a similar set of processes at the micro and macro levels. The next step then must be to fully consider the range of mechanisms that may potentially influence the impact of any one action in any particular type of consumption or production activity to save energy on total energy use at the geographical level of interest. Geographical focus will depend on whether the case under study involves a single national economy attempting to limit its total energy use and/or dependence on particular internal or external sources of energy supply, or to meet emissions reduction targets under international agreements, or whether global concerns, particularly the issue of climate change, are the subject of investigation.

However, the concern of this author is that as we extend our focus to consider a wider range of 'rebound' mechanisms, in addition to the challenge of how to analyse and model the problem in an integrated manner, we run into a very fundamental problem. This is how different effects and mechanisms may be treated within the simple rebound definition that relates 'actual energy savings' to 'potential energy savings'. An example of this problem has been considered in Section 4, where the potential for downward pressure on economy-wide energy use from increased efficiency in production or consumption activities was discussed. There we saw that, in the case of negative multiplier effects in energy supply, this only translates to downward pressure on rebound if these are considered within actual rather than potential energy savings.

This reflects a very basic problem in that there is a lack of agreement and clarity in the literature regarding how 'rebound' should be measured. This raises the question of how useful single measures of 'rebound' are when a wide range of potential and complex mechanisms need to be considered. In particular, the rebound has to date tended to neglect the issue of energy supply responses. This paper has highlighted the need to consider both price and quantity adjustments in energy supply markets. The response of energy suppliers to excess capacity and profitability in different time periods as demand for their output shifts may involve lowering or raising prices, which will further impact energy demand. Thus energy market effects may impact what have become accepted theoretical underpinnings for a single rebound measure. In particular, lower prices in energy markets may confound the zero rebound condition while higher prices cast uncertainty on the 100% rebound condition identified by Saunders (2000).[5] Should these reference conditions for rebound be reconsidered in light of energy market effects or does the notion of a single measure become less useful as multitude of determining factors are identified?

Generally, the identification of solid theoretical foundations for the range of mechanisms governing rebound effects is surely as, if not more, important than developing the empirical models and analyses that policymakers are so hungry for. This then raises the further question of whether the focus on empirical measurement of a 'rebound' effect has become a distraction from actually understanding and explaining how energy efficiency improvements work and impact on the wider economy.

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[5] The author is grateful to an anonymous referee for identifying this point.

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