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A Child's Guide to Energy Intensity and Energy Efficiency

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Abstract

This paper focusses on ambiguities in the discussion of energy efficiency linked to the fact that energy is typically combined with other non-energy inputs to generate energy-using services. An important potential source of misunderstanding concerns the different measures of energy efficiency. We draw here a clear distinction between energy effectiveness (also known as energy augmenting technical change) and energy intensity. In this discussion we stress the importance of various forms of endogenous substitution in determining changes in energy intensity following improvements in energy effectiveness. We also analyse the potential impact on energy intensity of improvements in the effectiveness of non-energy inputs. Finally, we explore the treatment of the costs of activating energy saving technology embodied in capital equipment.

1. Introduction

Concern over energy use often reflects the presence of environmental constraints that are not appropriately represented by the market mechanism. Under these conditions, market-driven decisions are suboptimal and allocative efficiency can be improved by restraining energy use. In a simple standard analysis this involves trading off environmental improvements against the provision of other goods and services so that measured GDP will fall. In short, whilst the environment benefits, other public and private consumption is reduced.[1]

Human welfare and environmental quality are intimately related through impacts such as climate change and air pollution. But whilst the costs of environmental action occur in the present, the benefits are often in the future and might be difficult to quantify categorically. Against this background, improvements in energy efficiency have been advocated as a means of avoiding any perceived conflict, with technological improvements in energy use being portrayed as a dynamic driver of economic green growth.

A correct understanding of the potential impact of improvements in energy efficiency therefore becomes a key requirement for a successful environmental energy policy. However, there are ambiguities and misconceptions in the literature in the way in which energy efficiency improvements are discussed, identified, and measured. Two quite separate phenomena are commonly referred to as improvements in energy efficiency and it is extremely important that these should be distinguished. To clarify the discussion, we refer to one as an increase in energy effectiveness or energy-augmenting technical change. The other is a reduction in energy intensity which we also call an increase in energy productivity.

Energy-augmenting technical progress is defined as an increase in the level of useful energy services that are supplied by a given physical amount of energy (Proskuryakova and Kovalev, 2015).[2] It implies that with all other inputs held constant, a greater output could be produced with a given input of energy or the same output with a lower input of energy. It is this conception of energy efficiency that is necessarily to generate the rebound and potential backfire phenomena, and which also lies behind attempts to link improvements in the environment to green growth.

However, many empirical studies use a different definition of energy efficiency. The IEA (2020, pp. 15,16) describe technical energy efficiency as "the ratio of energy use per unit of activity or services provided by energy-using technologies, such as buildings, appliances and equipment, industrial equipment and processes, and vehicles." They give as an example "a car that uses 1 litre of fuel to travel 20 kilometres is more technically efficient than one that uses 2 litres of fuel to travel 20 kilometres." We label this notion as a reduction in energy intensity, or an increase in

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[1] This does not necessarily occur. See, for example, the double dividend literature concerning the imposition of carbon taxes.

[2] It is a concept that can be applied to any input. For example, in the standard economic growth literature labour- and capital-augmenting efficiency improvements are known, respectively, as Harrod and Solow neutral technical change.

energy productivity. The issue is that in the energy intensity measures there is no requirement to hold other inputs constant.

Whilst it is clearly confusing to have alternative metrics given the same name, the problem is more serious. One measure is not an approximate surrogate for the other. There are various ways that reductions in energy intensity can be achieved and only some involve increased energy effectiveness. Also improved energy effectiveness can lead to increases in energy intensity; energy-augmenting technical change can reduce energy productivity.

In the present paper we stress the implications of two key features of energy use which affect energy effectiveness and intensity outcomes, sometimes producing complex and counter-intuitive impacts. The first is that energy almost never operates alone; rather it typically combines with other inputs to supply energy-using services to households or firms. An example is that gas, together with a boiler, heats space; it is the warmth that we desire not the gas as such. The second is that there are typically multiple techniques for producing the same energy-using service. We therefore generally have a choice between how the energy-using service is to be provided. These two features interact to produce the problems already indicated.

In discussing these two features we seek to shed some light on:

- The difference between energy intensity and energy effectiveness.
- The importance of endogenous substitution in determining energy intensity following changes in energy effectiveness.
- The impact of improvements in the effectiveness of non-energy inputs in the production of energy-using services.
- The costs of activating improvements in energy effectiveness where this requires investment.

The treatment here is conceptual but presented in a non-technical manner. Section 2 is a brief overview of the literature. Section 3 defines and compares alternative measures of energy efficiency. Section 4 discusses the choice of production technique where there are available alternatives. Section 5 outlines the impact of energy-augmenting technical progress which operates across all the alternative techniques in a given technology. Section 6 analyses the impact on energy use of changes in the effectiveness of the non-energy input. Section 7 looks at the implications of energy-augmenting improvements delivered through changes in capital equipment. Section 8 investigates the cost of implementing improvements in energy effectiveness. Section 9 is a short conclusion.

2. Literature review

There is an extensive literature on improving energy efficiency. In this paper we focus on some examples where the definition and measurement of energy efficiency is both crucial for the analysis and is potentially problematic.

There is a large body of work that looks at the economic impact of energy-augmenting technical change, normally concentrating on rebound and potential backfire (Chitnis and Sorrell, 2015; Druckman et al., 2011; Duarte et al., 2018; Figus et al., 2017; Frondel et al., 2012; and West, 2004). Rebound is the phenomenon whereby the expected reduction in energy use brought about through increased energy effectiveness is partly frustrated by accompanying endogenous economic decisions (Khazzoom, 1988). In some cases, the impact of these accompanying decisions can be so large that energy use actually increases and this is known as backfire. In this literature, one commonly used measure of energy efficiency, reduced energy intensity, can potentially move in an opposite direction to the improvement in energy effectiveness. As argued in the introduction, the problem is that energy usually combines with other inputs to provide energy-using services. It is the endogenous changes in the use of other inputs that creates the difficulty.

A small number of papers address this issue by specifically attempting to model energy-using consumer services as a combination of physical energy and technology (Borenstein, 2015, Fikru et at., 2018, Gillingham et al., 2016, Haas et al., 2008; Hunt and Ryan, 2015; and Walker and Wirl, 1993). But these papers are limited in that the technology only acts as a linear conduit that converts physical energy into an energy-using service. Improved energy effectiveness is modelled simply as a reduction in the coefficient linking energy input to the service output. In this approach, by construction, energy effectiveness and the energy intensity are directly inversely related. An increase in energy effectiveness is modelled as a reduction in energy intensity; there is no conceptual or practical distinction drawn between them.

Two papers attempt to analyse in a fuller, more-conventional, manner the provision of energy-using services. Bye et al. (2018) models the domestic provision of housing services as a composite of energy use and dwellings. However, this work defines energy efficiency as a cap on residential energy use, essentially focusing on external limitation on the energy intensity of domestic heat rather than energy effectiveness improvements in the domestic production of that heat. Figus et al. (2018) consider explicitly the impact of motor-vehicle-augmenting technical change on economy-wide petrol and diesel use in private transport. The paper demonstrates how the energy intensity of private transportation might fall when the effectiveness of motor vehicles improves without directly influencing the effectiveness of fuel use. An example would be technical change which meant that the vehicle lasted longer with reduced maintenance costs.

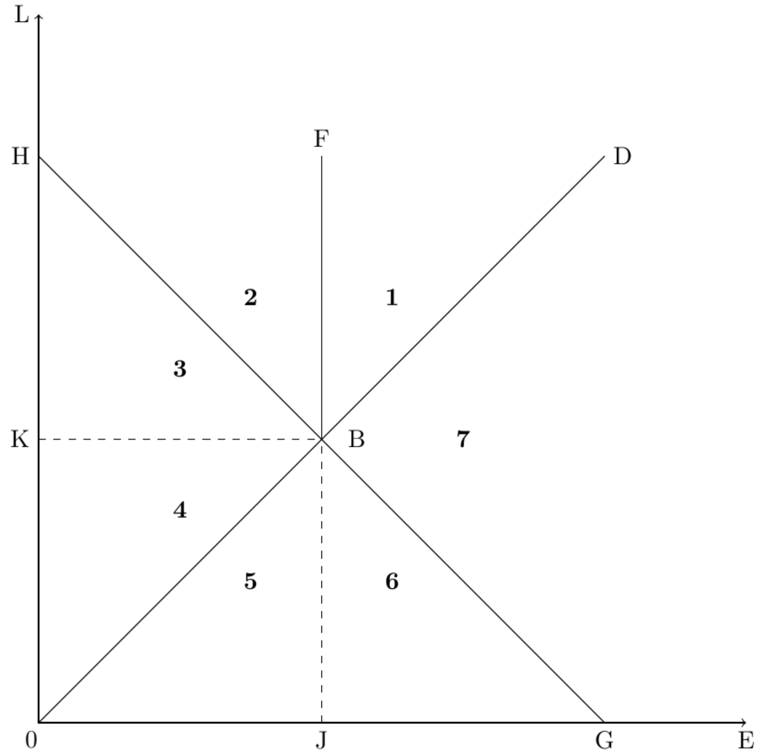
Another strand of the literature discusses the empirical estimation of the so-called "Porter hypothesis" whereby stringent environmental regulation could induce innovation and energy efficiency (Porter and Van der Linde, 1995). Papers in this literature, such as Boyd and Pang (2000) and Montalbano and Nenci (2019) estimate this relationship empirically using energy intensity or its inverse as a measure of energy efficiency. Whilst they acknowledge its drawbacks, they find intensity to be a convenient measure due to data availability and conventions in the literature.

3. Basic definitions

The literature above introduced in an informal way two measures associated with energy efficiency and shows how these may differ in different strands of research. We want to illustrate these with more precision and focus on a total of four metrices. These are energy-augmenting technical progress, which we also refer to as energy effectiveness; economic efficiency; reduced energy intensity, which we also call energy productivity; and the non-energy/ energy input ratio.

To illustrate this, we use as an example the production of a given amount of light using as inputs lightbulbs, L, and electricity, E.[3] In Figure 1, the electricity and lightbulbs needed to produce this output for a particular technique are indicated by the co-ordinates on the E and L axes. Here B is the initial reference technique with inputs of J electricity and K light bulbs. We use Figure 1 to compare the energy efficiency of other techniques producing the same light output as technique B.

Figure 1. The evaluation of techniques, compared to B, using different indices of energy efficiency



The most straightforward concept is technical efficiency; any technique whose unit inputs are represented by a point in the area 0KBJ is technically more energy efficient than technique B. This means that a unit of light can be produced with less electricity and the same, or fewer, lightbulbs than technique B. This is the fundamental essence of efficiency – more output can be produced with the same or less inputs.

A second notion is energy intensity and its inverse, energy productivity. Any point to the left of line FBJ, classified here as the area 0HFJ, has lower energy intensity, and higher energy productivity, than technique B. Energy intensity is simply the unit energy input; any point to the left of B uses less energy to produce a unit of light than technique B. Energy productivity is typically defined as the output, here light, produced for each unit of energy used as an input. This is just the inverse of the energy intensity. Therefore, a proportionate reduction in energy

[3] However, the analysis is transferable to the provision of any domestic or industrial energy-using service.

intensity generates an equal proportionate increase in energy productivity.[4] Note that neither energy intensity nor productivity, as defined here, consider the level of lightbulb input.

A third independent measure of energy efficiency is the non-energy/energy input ratio. This measures the use of energy relative to other inputs. An increase in this ratio is sometimes taken as an improvement in energy efficiency; it is taken as an alternative measure of energy intensity. On this metric all techniques that had unit input combinations to the left of the line 0BD would be considered more energy efficient than B. These are points in the area 0HD.

Finally, there is economic efficiency. Imagine that there is a line, here represented by the HBG, which passes through point B and gives all the combinations of electricity and lightbulbs that can be purchased for the same total cost as input combination B. This is the unit iso-cost line.[5] All combinations of unit inputs which lie in the area 0HBG have a higher economic efficiency than B. Calling these techniques more economically efficient rests on the notion that they would use fewer resources, when those resources are valued at their present prices.[6] That also means that techniques with unit inputs in this area have a lower unit cost at the present ruling input prices than does technique B.

It is self-evident that these different measures are not, in principle, even approximately the same: Figure 1 can be thought of as a rather complex Venn diagram with a number of intersecting sets. We partition Figure 1 into seven separate areas, numbered 1 to 7. Table 1 then gives the status of techniques in each area, compared to technique B, as identified using each efficiency measure. This representation clearly reveals the existence of ambiguity. Only for techniques in area 4, KB0, do all measures record an increase in energy efficiency and only in area 7, DBG, is there an unambiguous reduction.

Table 1: The measured energy efficiency compared to point B in Figure 1.

Number	Area	Technical Efficiency	Economic Efficiency	Energy Productivity	Energy Ratio
1	FBD	X	X	X	√
2	HBF	X	X	√	√
3	HBK	X	√	√	√
4	KB0	√	√	√	√
5	0BJ	√	√	√	X
6	JBG	X	√	X	X
7	DBG	X	X	X	X

4 The formal relationship between the two measures is shown more fully in Appendix 1.

5 This iso-cost line is derived formally in Appendix 2. The appropriate way to cost the use of capital equipment and consumer durables is discussed in Section 7.

6 The cost-minimising technique is economically efficient if input prices accurately reflect scarcity, which includes the use of scarce natural resources. Introducing a carbon tax to appropriately cost carbon emissions, for example, will increase allocative efficiency, but will not, in itself, increase technical efficiency, which is the concern in this paper.

Note: √ and X represent yes and no respectively.

One energy policy ideal is to reduce energy intensity, that is increase energy productivity, by improving energy effectiveness. This could allow economic output to rise whilst energy use falls.[7] However, in subsequent sections we show that an increase in energy effectiveness is neither a necessary, nor sufficient condition for energy productivity to rise. We will be particularly interested in outcomes that occur in sections 2, 3 and 6.

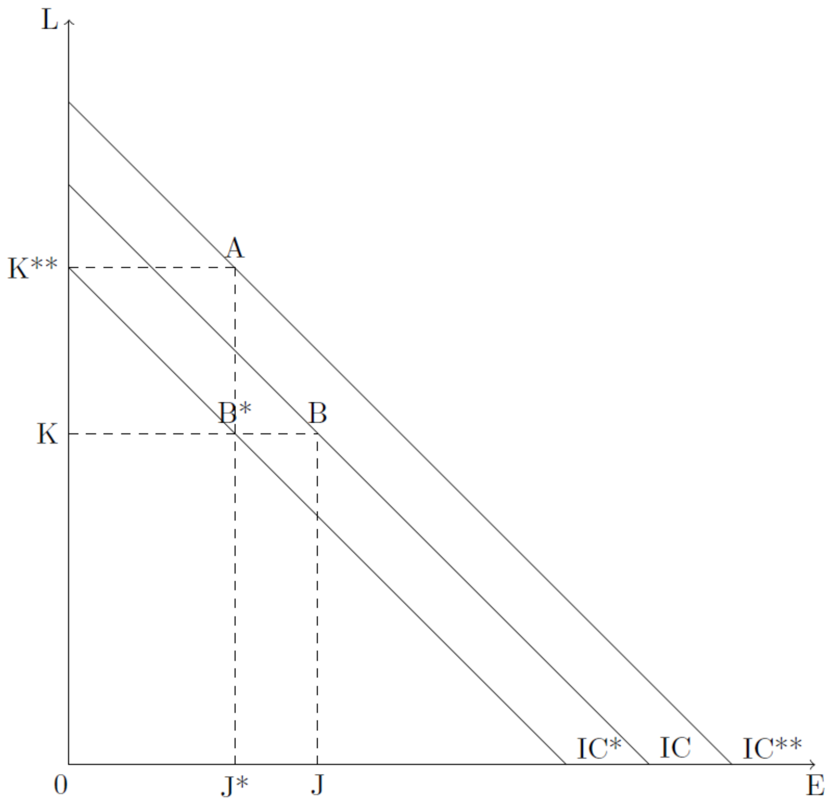
4. Choice of Technique

The previous section presented a taxonomy of the variously measured efficiency comparisons of alternative techniques. However, it did not deal with the key issue of how a technique is chosen for adoption and the implications of such a choice. It is useful to start by considering a pure increase in energy effectiveness that applies solely to technique B. This is represented in Figure 2 by a move from point B to B*. This involves a reduction in the unit electricity input from J to J* whilst the unit lightbulb input remains fixed at K. The new position will be on the iso-cost line IC*. This change is registered as an improvement on all the efficiency measures listed in Table 1.

A rational cost-minimising consumer or firm will voluntarily make the move from technique B to B*. This is because B* is on the lower iso-cost line, IC*, represents a lower unit cost. Two central elements of the energy efficiency literature depend on this characteristic. These are: the link between energy effectiveness and growth; and the rebound phenomenon, whereby the expected fall in the energy use from the gain in energy effectiveness is reduced because of endogenous income and substitution effects.

Figure 2. The difference between increased technical energy efficiency and energy productivity

[7] There are income effects not considered here that might frustrate this.



Compare the move to B*, made possible through increased energy effectiveness, with a change of technique aimed at reduced energy intensity (increased energy productivity) driven by an imposed administrative restriction, such as an energy intensity mandate. For the same reduction in unit energy use, the implications of the two options are quite different. A technique imposed to reduce energy intensity would be in segment 2, HBF, in Figure 1. An example, in Figure 2, is A with unit inputs J*, K**. In this case, firms and households are being manipulating or forced to adopt a technique which was not the chosen, cost-minimising, technique at the existing ruling prices. Instead of the unit cost falling, it will, in this case, rise; the new isocost line is IC**. Although at A the electricity input is lower than at B, the lightbulb input is much higher. This has consequences for the ease of implementation of the policy and growth that are quite the opposite of those generated by the improvement in energy effectiveness. Further, there are no rebound effects with such changes in energy intensity.[8]

It is often the case that accompanying the efficiency improvement represented by the move from B to B*, the associated rebound effect is identified as the indirect impact driven by the subsequent increase in disposable income. Improvements in the effectiveness of inputs lead to a reduction in the cost of energy-using services. Consequently, after paying for these services consumers will have additional income to spend directly on energy (direct rebound) and on other goods and services whose production will involve energy use (indirect and economy wide rebound) We do not consider such impacts here but they are typically a relatively minor source of rebound (Lecca et al. 2014). A more important consideration is the substitution possibilities

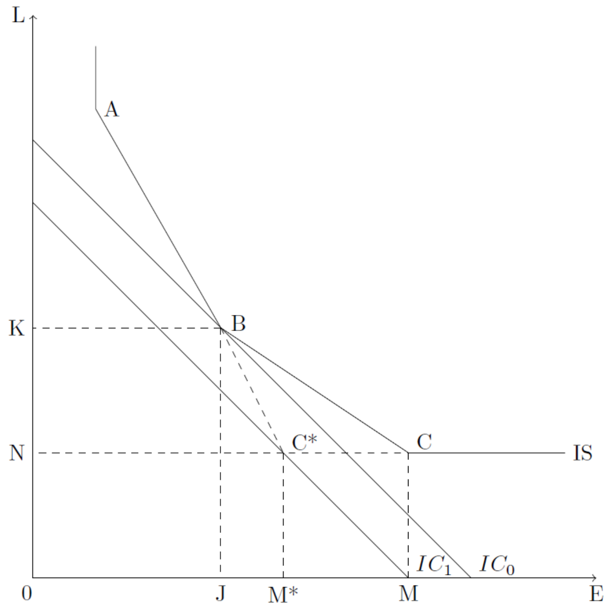
[8] It is important to stress, reinforcing the comments in footnote 4, that this does not imply that regulation is necessarily allocatively inefficient.

that the efficiency improvement typically allows. For this we need to consider the existence of a range of alternative techniques; that is to focus on a technology, not just a single technique.

5. Technologies and techniques

In studying production, economists typically consider not just one technique but a technology, which comprises a set of techniques.[9] These are a group of alternative ways to produce a given output. A central concern for economists is choice, and this not only covers consumption choices but also choice amongst techniques in production. In this respect, changes in energy effectiveness that apply to the delivery of an energy-using service required to meet production or consumption needs are analysed as potentially operating on any of the individual techniques that can deliver that service.

Figure 3. Increase in the technical energy efficiency of individual techniques in a technology



Three separate initial techniques are identified in Figure 3; A, B and C. Together with linear combinations they make up the unit isoquant, IS. The unit isoquant represents combinations of inputs that can produce one unit of output and it connects adjacent points, such as B and C, with straight lines. Points along line BC therefore represent hybrid techniques which are a weighted combination of techniques B and C. A similar situation holds for points on lines AB in relation

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[9] These are usually expressed in terms of a production function (Heathfield and Wibe, 1987))

to techniques A and B.[10] Initially the iso-cost line IC_0 identifies B as the cost minimising technique.[11]

In Figure 3 improvements in the effectiveness of inputs are represented by shifts in the individual techniques that make up the unit isoquant. This allows the analysis of the impact of increases in energy effectiveness that apply not across the whole technology but just to specific techniques. If there were an increase in energy effectiveness that applied solely in technique B, the analysis would be essentially the same as in Figure 2. Technique B would now use less energy and its dominance over the other techniques would be enhanced. The service would be provided at lower cost and with reduced energy intensity.

However, imagine an increase in the energy effectiveness that applied only to the most energy intensive technique, C, that shifts the unit inputs to point C* but has no impact on the other techniques. At the existing input prices, C* would now replace B as the least-cost technique with the iso-cost line falling to IC*, with unit inputs M*, N. Note that the energy intensity of production has risen - that is, $M^* > J$. Similarly, the ratio of energy to non-energy inputs is now higher. Even if there is no income effect and the output of the service remains the same, energy use will rise. This is a form of backfire.

Finally consider technique A, the least energy intensive of the three. In the specific construction of Figure 3, there is no improvement in energy effectiveness that at existing input prices will make this the least-cost technique. The lightbulb cost alone makes the technique unviable at existing prices. However, note that an improvement in light bulb effectiveness, with no change in the electricity effectiveness, could lead to technique A being the most preferred, and therefore energy intensity falling. This is an issue to which we return in Section 6.

Up to now, in this section the cases discussed have been chosen to highlight the complexity that is introduced where there are alternative techniques for delivering a particular energy-using service. But it might be thought that the outcome relating to technique C is the result of some trick in the sense that the increase in energy efficiency is so selective. In fact, an increase in energy effectiveness would not typically be analysed in this way. Rather, economists normally consider a situation where the energy effectiveness in all the techniques which comprise a given technology is simultaneously increased by the same proportionate amount. That is to say, the increase in energy effectiveness applies across the whole technology. This is illustrated in Figure 4.[12]

We take as an example a 100% increase in the effectiveness of the energy input. For each of the techniques A*, B*and C* the electricity input is a half its original value. The isoquant shifts from

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[10] In Figure 3 there are likely to be many available techniques above the line ABC. However, these will all be technically inferior to the techniques A, B or C, or linear combinations of these techniques. All these technically inferior techniques will have higher costs than at least some of the techniques on the unit iso-quant and can therefore be ignored in this analysis.

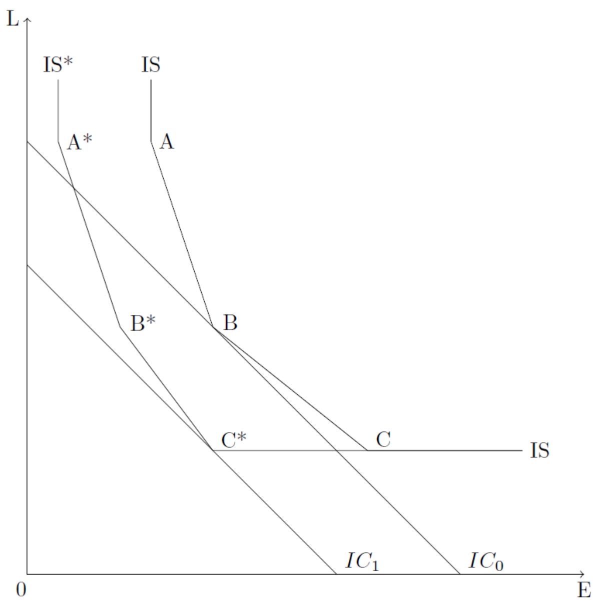
[11] This is the lowest iso-cost line that is consistent with producing a unit of output. More details are given in Appendix 1.

[12] The relationship between output and the two inputs is typically represented as convex, continuous, and differentiable. Essentially, an infinite number of possible techniques are assumed to be available. This allows the more straightforward application of optimising methods, and this is outlined in more detail in Appendix 3

ABC to A*B*C*, so that it moves inwards, to the left, and becomes steeper. Because of the specific discontinuities in the isoquant in Figure 4, there are in general two possible outcomes of such an energy-effectiveness improvement: one of the two new techniques B* or C* will be chosen.

If it is B*, then the energy unit input would fall by the full amount of the effectiveness gain; no rebound effects would be experienced in terms of the choice of technique.[13] However, in the situation as shown in Figure 4, the new cost minimising choice is C*, with the new minimum iso-cost line IC*. This means that the reduction in energy intensity is less than the increase in energy effectiveness so that rebound occurs. In fact, with the parameters implicit in the construction of Figure 4, back-fire occurs, as in Figure 3. Moreover, where more techniques are included, so that the unit isoquant becomes smooth, the reduction in energy intensity will always be less than the increase in energy effectiveness; some rebound will always occur though of course, not necessarily backfire. For more details see (Dimitrooulos, 2007; Sorrell and Dimitrooulos, 2007)).

Figure 4. A 100% increase in the technical energy efficiency that applies to all techniques



6. Improvements in the efficiency of the non-energy input

It is of interest to consider the impact of increases in the effectiveness of non-energy inputs in the production of energy-using services. In the case of the generation of light, an example would be technical change that allows the same amount of light to be produced with the same electricity input, but a smaller light bulb or a lightbulb that lasted for a longer period of use.

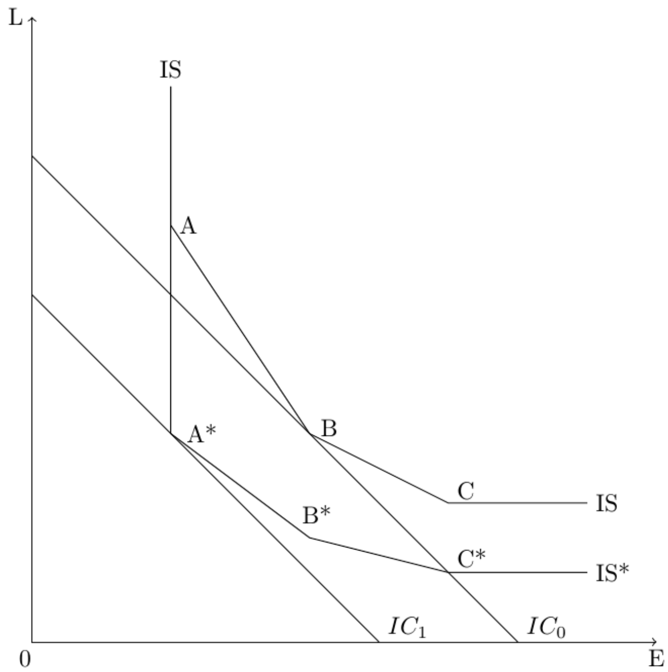
We take the same kind of approach as in Section 5, which we represent in Figure 5. In this case the initial cost-minimising technique is again B, but there is now a 100% improvement in the

[13] There would also be a fall in the price of the energy-using service and this would typically produce indirect rebound effects, but again these are abstracted from here.

effectiveness of the lightbulbs[14]. This means for every technique the lightbulb intensity is reduced by 50%. The unit isoquant shifts from IS to IS*; it moves downwards and now becomes flatter.

Again, there are two possible outcomes for the choice of technique. In some cases, because of the kink in the isoquant at B, the choice will be B*. However, an alternative is as in Figure 5 where the cost-minimising choice is now A*. Note that whilst the only change that has been made is to increase the effectiveness of the lightbulb, because of this efficiency increase, users endogenously choose a less energy-intensive technique.[15] This produces the following seemingly paradoxical result. For high enough values of the elasticity of substitution between inputs, even with output fixed, an increase in energy effectiveness could produce backfire and therefore an increase in energy intensity. However, an increase in the effectiveness of the non-energy input applied across all techniques will never increase, and will typically reduce, the energy intensity.

Figure 5. A 100% increase in the technical efficiency of non-energy inputs



This means that because of endogenous substitution effects, simply observing, ex post, that the energy intensity has fallen as a result of introducing a change in productive efficiency is no indication of whether the technical change embedded an increase in energy or non-energy effectiveness. It also highlights the difference between energy effectiveness and energy productivity (as measured by the inverse of energy intensity). An increase in the effectiveness of non-energy inputs will reduce energy intensity. This implies an increase in non-energy effectiveness increases measured energy productivity although there has been no change in energy effectiveness. Note also that here the standard notion of the rebound effect is non-

[14] Note that this is not equivalent to an improvement in energy effectiveness embodied in a change in the lightbulb. This is the equivalent of an improvement in productive effectiveness that reduces the unit cost of the lightbulb itself. This is dealt with in more detail in Section 7.

[15] With a smooth isoquant there will always be a move to a less energy intense technique.

operative; there is no prior technically determined "expected" proportionate change in energy use as a result of this non-energy improvement in efficiency.

7. Embodied technical change and investment.

Many of the energy (and non-energy) improvements in effectiveness will be embedded in the capital equipment or consumer durables that are used, together with energy, to provide energy-using services. In terms of the example used in Section 5, this would imply that changes in the lightbulb could embody improvements in the effectiveness of either or both energy and non-energy inputs. Similarly, in the delivery of transport and domestic heat, an improvement in energy effectiveness is likely to be produced through changes in the vehicle or boiler. An improvement in energy effectiveness does not necessarily come about through qualitative changes to the energy input; it is often delivered through changes in the other (non-energy) input.[16]

For example, imagine that an improvement in the construction of insulation means that the same insulation properties can be achieved with less material. This would be an increase in insulation efficiency, as discussed in Section 5. For a particular technique, this would mean a given temperature would be achieved with the same energy input but less insulation. On the other hand, suppose that the technical change in insulation improved the effectiveness of energy to heat space. Although this is a technical change that applies to the non-energy input, it actually increases the effectiveness of the energy input. Again, for a specific technique a given temperature level could now be achieved with the same insulation but less energy, as in Section 4.

In the previous section we discussed the importance of knowing whether an efficiency improvement is energy or non-energy augmenting, especially in the presence of possible substitution between inputs in the production of energy-using services. We argued it is difficult ex post to know whether a technical change is energy or non-energy efficiency augmenting by simply observing the outcome. This is because in all cases it is most likely that there will be reductions in the unit intensities of both inputs. The discussion in the present section has up to now simply extended the nature of the problem. Here we are arguing that there is no one-for-one correspondence between the input that has been changed by the technical advance and the input whose efficiency has been improved by that advance.

8. The cost of implementing efficiency improvements

The observation that efficiency improvements of all types are often realised as changes in capital equipment or consumer durables raises a separate concern. This is an issue that proves a potential source of misunderstanding between the different disciplines involved in energy policy. Economists often treat improvements in energy effectiveness as a costless technology shock (CTS). This assumption is made so as to focus the analysis on the final outcome of the efficiency improvement. However, to many practitioners the process of introducing and implementing

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[16] The same observation can be made about improvements in non-energy effectiveness. This might come about through qualitative changes to the energy input. For example, in the provision of transport services, improvements in fuel characteristics might reduce engine wear so that a change to the fuel improves the efficiency of the vehicle input.

efficiency improvements is costly and a key element of the analysis. Further, once these costs are identified, there then can follow the judgement that they partly or wholly offset the impact that energy savings can have on discretionary income and therefore limit the potential economic stimulus that increased energy effectiveness might entail.

There are potentially three types of cost that could be invoked here. The first is that to attain and apply the knowledge that underpins an improvement in energy effectiveness, major expenditures on research and development, R+D, might be involved. This requires the use of scarce resources that could be funded by government, the not-for-profit or private sector sources. In assuming that improvements in energy effectiveness are costless, economists are not claiming that R+D costs do not occur. Nor are they arguing that these should not be included in a comparative evaluation of policies to reduce energy use via technical change as against other policies, such as tax or cap and trade for example. Rather they are saying the analysis of the adjustments required to accommodate efficiency changes, such as the possible rebound and backfire effects, is conceptually separate from the considerations that drive R+D expenditure. The implicit argument here is that these R+D costs are real and can be significant but just need a separate analysis.

A second possible cost source is where, as highlighted in Section 7, the increase in energy effectiveness is incorporated in (domestic) capital equipment. In these cases, investment is required in order to access the efficiency gains and this is sometimes identified as an additional cost. In our view, if the exogenous change is purely an improvement in energy effectiveness, this is a misinterpretation particularly if the focus of the analysis is the long run, the period where all adjustments can be made to accommodate the efficiency gain. The argument is as follows.

In the provision of energy-using services, firms or households often have to employ an input which deliver productive services over an extended period of time, such as machines, buildings, boilers and vehicles – domestic and industrial capital goods. The cost minimising choice, including the choice of the size and type of the capital good, can be made using the isoquant analysis outlined in Section 4. In this case, the cost of the capital services is the interest payments plus depreciation of this capital. An alternative is to think about the firms or households renting this equipment, in the same way that it was common to rent colour TV sets in the UK in the 1970s.[17]

In this approach, there is no additional investment; when it comes to the replacement of the existing capital, the new vintage is adopted with the improved efficiency. If there are gains to input effectiveness the unit cost must be reduced, so that there is no extra cost. There might be transitional issues in that it might be cost minimising for firms or households to choose to replace their equipment more rapidly to access to gains in the energy effectiveness sooner, but this would seem to be an advantage rather than a disadvantage. Similarly, if as a result of the efficiency gains the price of the energy-using service falls, some firms who are still using the old technology might

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[17] In the production function used in Fullerton and Ta (2019) and Gillingham et al (2016) the capital cost are treated simply as a cost required to reach a higher energy productivity. This is outlined in Appendix 4.

suffer lower profits (essentially a reduction in economic rent on their existing machines) but this is offset by benefits to the consumer.

A third possible associated cost is that it might be thought that increased energy effectiveness implies or requires greater capital intensity. The key point is simply that such an outcome is not consistent with the conventional definition of energy augmenting technical change. In particular, as shown in Sections 4 and 5, in standard economic theory an increase in energy effectiveness that applies across all techniques will never increase capital intensity. Further, it is typically expected that increases in the effectiveness of either energy or non-energy inputs will reduce the unit intensity of both inputs.

However, an energy productivity improvement, that is a reduction in energy intensity, might be required to meet some regulatory standard, a so-called energy efficiency mandate. As argued in Section 3, if this is accompanied by an increase in unit-intensity of the other input, and would not have been adopted voluntarily, it is located in Section 2 of Figure 1. Such a move can be modelled as a simultaneous increase in energy productivity and a reduction in the productivity of the other input (Allan, 2009; Lemoine, 2020). However, such a move would increase unit cost and have none of the characteristics of a standard efficiency improvement.[18]

Finally in this section, we return to the issue of R+D. What if the firm itself or the industry collectively financed the research or even if a public provider charged users to recoup the cost? In these cases, the relevant decision is whether to undertake the initial R+D, with the cost of the R+D amortised as one of the non-energy costs. For the whole exercise to be counted as an improvement in efficiency, then the unit cost, including the amortised R+D, should fall. If that is not the case the technique will not be chosen voluntarily; we would be involved with a reduction in energy intensity imposed through some regulation or energy tax.[19]

9. Conclusions

In this paper we attempt to clarify some concepts and issues involved in investigating the impact of improving the efficiency with which energy-using services are produced, either in industrial or domestic settings. The paper focusses wholly on the standard case where energy and non-energy inputs are employed to produce energy-using service; each technique is produced with more than one input and there are a number of techniques in each technology. We also limit ourselves to dealing with situations in which the level of output of the energy intensive good or service is held fixed. We are therefore taking an extreme partial equilibrium approach, though the principles identified form a strong basis on which to expand the analysis to incorporate endogenous prices, outputs and a full general equilibrium model. We stress the fact that the existence of other inputs complicates the analysis of the impacts of energy efficiency, sometimes in counter-intuitive ways.

[18] In the case of (Allan, et al. 2009) and Lemoine (2020) the cost implications of the reduction in non-energy efficiency just offsets the cost benefits of the energy efficiency improvements, so as to neutralise and impact on the demand for the energy intensive good or service but this an ad hoc assumption.

[19] The issue of risk and uncertainty involved in R+D expenditure clearly complicates the analysis.

A major aim of the paper is to discuss the relationship between the various measures of energy intensity, energy productivity, energy effectiveness and economic efficiency. We show that an increase in energy augmenting efficiency is neither a necessary nor a sufficient condition for a reduction in energy intensity in this context. The analysis stresses the importance of various forms of endogenous substitution in determining changes in energy intensity subsequent to changes in prices, regulation and improvements in both energy and non-energy efficiency.

Typically, capital goods (or in the domestic setting, consumer durables) are an important non-energy input in the production of energy-intensive goods and services and energy efficiency improvements are often embedded in their design. We argue that financing and replacement costs of this capital should be amortized, and their treatment be like any other input. There is in principle no additional investment cost that should offset the cost reduction that real efficiency improvements should provide.

The definition and analysis of efficiency improvements in the production of energy-intensive goods and services is not a straightforward issue. We here have attempted to present the topic from an economic perspective using extremely stylised models. The issues raised are important because key aspect of the impact of improvements in energy efficiency, including the effect on growth and the existence of rebound, depend on an appropriate definition. It is not surprising that there are ambiguities and misunderstandings, particularly as this is a field shared by researchers, analysts, and policymakers from a range of backgrounds.

References

Allan, G., Hanley, N., McGregor, P., Swales, 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. doi:10.1016/j.eneco.2006.12.006

Borenstein (2015), A Microeconomic Framework for Evaluating Energy Efficiency Rebound and Some Implications. The Energy Journal, 36 (1): 1-23

Boyd G.A., Pang J.X. (2000), Estimating the linkage between energy efficiency and productivity Energy Policy, 28 (5), 289-296

Bye B., Fæhn T., Rosnen O. (2018). Residential energy efficiency policies: Costs, emissions and rebound effects. Energy, 143:191-201.

Chitnis, M. and Sorrell, S. (2015). Living up to expectations: Estimating direct and indirect rebound effects for UK households. Energy Economics, 52:S100-S116.

Dimitrooulos, J. (2007). Energy productivity improvements and the rebound effect: An overview of the state of knowledge. Energy Policy, Vol. 35, N.12, pp. 6354–6363.

Druckman, A., Chitnis, M., Sorrell, S., and Jackson, T. (2011). Missing carbon reductions? Exploring rebound and backfire effects in UK households. Energy Policy, 39(6):3572–3581.

Duarte, R., Feng, K., Hubacek, K., Snchez-Chliz, J., Sarasa, C., and Sun, L. (2016). Modeling the carbon consequences of pro-environmental consumer behavior. Applied Energy, 184:1207 – 1216.

Duarte, R., Snchez-Chliz, J., Sarasa, C., and Sun, L. (2018). Consumer-side actions in a low-carbon economy: A dynamic CGE analysis for Spain. Energy Policy, 118:199 – 210.

Figus, G, Turner, K, McGregor, P & Katris, A (2017). Making the case for supporting broad energy efficiency programmes: impacts on household incomes and other economic benefits. Energy Policy, vol. 111, pp. 157-165.

Figus, G., Swales, J. K., & Turner, K. (2018). Can private motor vehicle-augmenting technical progress reduce household and total fuel use? Ecological Economics, 146, 136-147. DOI: 10.1016/j.ecolecon.2017.10.005

Fikru M. G, Gelles G., Ichim A., Kimbal J. W., Smith J. D., Zawodniok M. J. (2018). An economic model for residential energy consumption, generation, storage and reliance on cleaner energy, Renewable Energy,119,429-438.

Frondel, M., Ritter, N., and Vance, C. (2012) Heterogeneity in the rebound effect: Further evidence for Germany. Energy Economics, 34(2):461-467.

Fullerton, D. and Ta, C. L. (2019), Costs of Energy Efficiency Mandate Can Reverse the Sign of Rebound", University of Illinois at Urbana-Champaign, Selected Paper prepared for presentation at the 2019 Agricultural and Applied Economics Association Annual Meeting Atlanta, GA, July 21-July 23, 2019.

Gillingham, K., Rapson, D. and Wagner, G. (2016), "The rebound effect and energy efficiency policy", Review of Environmental Economics and Policy, vol. 10, pp. 68-88.

Haas, R., Nakicenovic, N., Ajanovic, A., Faber, T., Kranzl, L., Müller, A., and Resch, G. (2008). Towards sustainability of energy systems: A primer on how to apply the concept of energy services to identify necessary trends and policies. Energy Policy, 36(11):4012–4021.

Heathfield, D. F. and Wibe, S. (1987). An Introduction to Cost and Production Functions, Palgrave.

Hunt, L. C. and Ryan, D. L. (2015). Economic modelling of energy services: Rectifying misspecified energy demand functions. Energy Economics, 50:273–285.

IEA (2020), Energy Efficiency 2020, IEA, Paris https://www.iea.org/reports/energy-efficiency-2020

Khazzoom, D. (1988). Energy Saving Resulting from the Adoption of More Effcient Appliances. The Energy Journal, 8(4):85-89.

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

Lemoine, D. (2020), General equilibrium rebound from energy efficient innovation, European Economic Review, vol. 125, pp. 1-20.

Montalbano P, Nenci S (2019) Energy efficiency, productivity and exporting: firm-level evidence in Latin America. Energy Economics 79 97-110.

Luntz, F. (2007), Words that work: it's not what you say, it's what you hear, Argues that "*Efficient* and *efficiency* also have a positive intellectual tone [for Americans], suggesting the wise use of energy, resources, and so on. By comparison, *conserve* and *conservation* ... sounds austere." p. 252

Porter ME, Van der Linde C (1995) Toward a new conception of the environment–competitiveness relationship. J Econ Perspect 9 (4) 97–118.

Proskuryakova L., Kovalev A. (2015), Measuring energy efficiency: Is energy intensity a good evidence base?, Applied Energy, 138, pp. 450-459

Saunders, H. D. (2000). A view from the macro side: rebound, backfire, and Khazzoom Brookes. Energy Policy, 28(6):439–449

Sorrell, S. (2007). The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. Technical Report 4, UK Energy Research Centre.

Sorrell, S. and Dimitropoulos, J., (2007). The rebound effect: microeconomic definitions, limitations and extensions. *Ecological Economics*, 65 (3), 636–649.

Stern, D. (2020). How large is the economy-wide rebound effect?. Energy Policy.147 111870

Turner, K. (2013). "Rebound" effects from increased energy efficiency: A time to pause and reflect. Energy Journal, 34:25–42

Walker, I. O. and Wirl, F. (1993). Irreversible Price-Induced Efficiency Improvements: Theory and Empirical Application to Road Transportation. The Energy Journal, Volume. 14(4):183–205.

Wei, Taoyuan and Yang Liu (2017), Estimation of global rebound effect caused by energy efficiency improvement, Energy Economics, Vol. 66, pp. 27-34.

West, S. E. (2004). Distributional effects of alternative vehicle pollution control policies. Journal of Public Economics, 88:735–757.

Appendix 1

Energy intensity is $\frac{E}{Y}$and we define energy productivity here as $\frac{Y}{E}$. This means that:

(A1.1) $\frac{Y}{E} = \frac{1}{E/Y}$

Expression (A1.1) shows energy productivity as the inverse of energy intensity. Also implied is:

(A1.2)$\frac{d(Y/E)}{dt} = \frac{1}{(E/Y)^2}\frac{d(E/Y)}{dt}$

Equation (A1.2) can be rearranged as:

(A1.3)$\frac{d(Y/E)}{dt}\frac{1}{Y/E} = \frac{d(E/Y)}{dt}\frac{1}{(E/Y)}$

A proportionate change in energy intensity is the negative of the proportionate change in energy productivity.

Appendix 2: the iso-cost line

Where the total cost is C and the prices of electricity and lightbulbs are p_E and p_L, the set of electricity and lightbulb unit inputs that can be purchased is given as:

(A2.1) $C = p_E E + p_L L$

Equation (A2.1) can be re-written as

(A2.2) $L = -\left[\frac{p_E}{p_L}\right] E + \frac{C}{p_L}$

This implies that the intercept on the vertical (lightbulb) axis is given by $\frac{C}{p_L}$ and the negative slope is the ratio of the input prices, $\frac{p_E}{p_L}$.

When the choice is made as to the least-cost technique in Figures 3, 4 and 5, it is the one that just touches the lowest possible iso-cost line. This is the one that has the lowest intercept n the lightbulb axis. Given that we assume the price of lightbulbs is unchanged, this represents the lowest total cost.

Appendix 3

The standard economics approach would be to take the relationship between the production of light, Q, and the inputs of electricity and lightbulbs to be a continuous well-behaved production function, expressed as:

(A3.1) $Y = Y(E, L)$

In this relationship:

$\frac{\partial Y}{\partial M} > 0, \frac{\partial Y^2}{\partial M^2} < 0$ where M = E, L. Also, if and if E or L = 0, Y = 0.

The standard, well-behaved production function represented by (A3.1) can be extended to incorporate input-augmenting technical progress. This is represented by the parameters a_E and a_L so that equation (A3.1) is rewritten as:

(A3.2) $Y = Y(a_E E, a_L L)$

Typically a_E and a_L are initially set to unity and an increase in efficiency in either input would involve increasing the relevant parameter to be greater than one. For example, a doubling of the efficiency of electricity would imply setting $a_E = 2$ and the unit isoquant would shift in the manner shown in Figure 4, except that the isoquant would now be smooth with no kinks. Similarly an adjustment to the lightbulb efficiency would shift the unit isoquant as shown in Figure 5.

Appendix 4

A common approach in the literature (Fullerton and Ta, 2019; Gillingham et al., 2016) is to specify the production function for the energy intensive service as given in the following example:

(A4.1) $Y = eE$

Here the energy-intensive service is the provision of light, Y, and the energy source is electricity, E, and e is the fixed energy productivity, $\frac{Y}{E}$.

Equation (A4.1) specifies what is essentially a Leontief production function with only one input, E, and a fixed coefficient. The first problem is that light production is dependent on their being lightbulbs. Moreover, in this literature marginal productivity pricing, together with equation (A4.1), identifies the price of the energy intensive service, p_Y, as:

(A4.2) $p_Y = \frac{p_E}{e}$

However, using this price what is clear is that the "revenue" generated by the "sale" of the energy intensive service is not enough to cover the use of resources. The income produced is only enough to to meet the expenditure on electricity; no income is covering the cost of lightbulbs.

The second problem is that the relationship between energy productivity and the lightbulb input is typically not spelled out. The increase in efficiency is simply identified as an increase in the value of e. What is missing is an equation such as:

(A4.3) $e = e(L)$

That is to say, the energy productivity is some function of the initial investment in capital or the consumer durable.

A third problem is that the approach implies the existence of economies of scale; output can be doubled whilst only doubling one input, that is energy, E. Using equations (A4.1) and (A4.3) in modelling industrial production is not consistent with perfect competition. Such a production function is typically used in the Dixit-Stiglitz models of imperfect competition in which equation (A4.2) would no longer hold.

The situation is perhaps more appropriate for the domestic production of energy-intensive services. In that case, the household's consumption decision can be modelled in the following way. Assume to begin with that there are two consumption goods; the domestically produced energy-intensive service, Y, and a composite of all other commodities, Z. The household initially has an income I and the prices of electricity, lightbulbs and the composite commodity, (p_E, p_L, p_Z) are given (potentially, but not necessarily, set in competitive markets).

The firm's decision model has two periods, but the fixed income covers the expenditure in both periods). In period 1 the household purchases a quantity of consumer durables, L. In period 2 the household divides its expenditure between electricity, E, and the composite commodity, Z. The electricity is used together with the lightbulbs to produce light. The energy efficiency of the lightbulbs depends on how much is spent on them. The expenditure in period 2 is made in order to maximise the households utility function but this also depends on the level of investment in lightbulbs in period 1.

In order to illustrate the decision we make assumptions about the nature of two relationships; first the link between energy productivity and the expenditure on lightbulbs, shown generically as equation (A4.3); and second, the nature of the household utility function. The energy productivity function takes the form:

(A4.4) $e = BL^b$where B > 0 and 1 > b >0.

This implies:

$\frac{\partial e}{\partial B}$> 0, $\frac{\partial e}{\partial b}$> 0, and $\frac{\partial^2 e}{\partial B^2}$ = 0, $\frac{\partial^2 e}{\partial b^2}$<0.

In equation (A4.4), the parameter B can be thought of as an efficiency parameter. The value of L determines the energy productivity but an increase in the value of B will increase the effectiveness of any given value of lightbulbs in delivering light. The consumer's utility, U, takes a Cobb-Douglas form and is given as:

(A4.5)$U = AY^a Z^{(1-a)}$

For a given level of disposable income, D, the indirect utility function gives utility as a function of the prices, p_L and p_Z, so that:

(A4.6) $U = U(p_Z, p_Y, D)$

The specific form of equation (A4.6) that corresponds to the utility function (A4.5) is given as:

(A4.7) $U = \frac{AD}{p_Y^a p_Z^{1-a} K}$

In equation (A4.8) K equals $\left[\frac{a}{1-a}\right]^{1-a} + \left[\frac{1-a}{a}\right]^{a}$ and the household's disposable income is given as:

(A4.8) $D = I - Lp_L$

We can substitute equations (A4.2), (A4.4) and (A4.8) into equation (A4.7). This gives:

(A4.9) $U = \frac{AB^a(I - Lp_L)L^{ab}}{p_E^a p_Z^{1-a} K}$

Equation (A4.9) presents the household utility as a function of only one choice variable, that is the expenditure on lightbulbs. This determines both the disposable income, energy productivity and therefore the price of the energy intensive service, here the provision of light. Differentiating equation (A4.9) with respect to L and setting the result equal to zero produces:

(A4.10) $\frac{\partial U}{\partial L} = \frac{AB^a}{p_E^a p_Z^{1-a} K}\left[(I - Lp_L)abL^{ab-1} - p_L L^{ab}\right] = 0$

This is solved by setting $(I - Lp_L)abL^{ab-1} - p_L L^{ab}$equal to zero and rearranging.

This gives:

(A4.11)$L = \frac{abI}{p_L(1+ab)}$

This implies that:

(A4.12) $L = \frac{abI}{p_L(1+ab)}$

Equation (A4.12) suggests that in order to maximise consumer utility, in this case the share of the initial household income spent on the lightbulbs is fixed, independent of the value of the initial income I or the efficiency parameter B. The subsequent disposable income would be divided between consumption of the light, Y, and the composite, Z, so that:

(A4.12) $Y = \frac{eaI}{(1+ab)p_E}, Z = \frac{(1-a)I}{(1+ab)p_Z}$

The expressions in (A4.12) reflect the fact that the disposable income is period two is divided between expenditure on light and the composite Z in the ratio a to (1-a). This has interesting implications for any increase in energy efficiency. From equation (A4.11) we know that this does not affect the share of initial income that is spent on lightbulbs. Therefore the energy productivity will increase by the full amount of the efficiency improvement. That is to say, in this case there is no direct rebound. However, the spending on the energy intensive service, which now solely covers the electricity input remains constant. Given that the price of electricity has not changed there is then 100% indirect rebound.

Energy intensity: Energy use per unit of activity. Lower/higher energy intensity could indicate that energy is being used efficiently/inefficiently but not always. For example, making steel is an energy-intensive process, but energy intensity varies between steel factories for a range of reasons.

Technical energy efficiency (technical efficiency): The ratio of energy use per unit of activity or services provided by energy-using *technologies*, such as buildings, appliances and equipment, industrial equipment and processes, and vehicles. For example, a car that uses 1 litre of fuel to travel 20 kilometres is more technically efficient than one that uses 2 litres of fuel to travel 20 kilometres. (IEA, 2020, pp. 15,16).