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UKERC Review of Evidence for the Rebound Effect

Supplementary Note: Graphical illustrations of rebound effects

Working Paper

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Preface

This report has been produced by the UK Energy Research Centre's Technology and Policy Assessment (TPA) function. The TPA was set up to inform decision-making processes and address key controversies in the energy field. It aims to provide authoritative and accessible reports that set very high standards for rigour and transparency.

This report forms part of the TPA's assessment of evidence for a **rebound effect** from improved energy efficiency. The subject of this assessment was chosen after extensive consultation with energy sector stakeholders. It addresses the following question:

What is the evidence that improvements in energy efficiency will lead to economy-wide reductions in energy consumption.

The assessment was led by the Sussex Energy Group (SEG) at the University of Sussex, with contributions from the Surrey Energy Economics Centre (SEEC) at the University of Surrey, the Department of Economics at the University of Strathclyde and Imperial College. The assessment was overseen by a panel of experts and is extremely wide ranging - reviewing more than 500 studies and reports from around the world.

The conclusions from this assessment are contained in the main report: *The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*. In addition to the main report, the outputs from the assessment include five in-depth *Technical Reports*, as follows:

1. Evidence from evaluation studies
2. Evidence from econometric studies
3. Evidence from elasticity of substitution studies
4. Evidence from CGE modeling studies
5. Evidence from energy, productivity and economic growth studies

Each Technical Report examines a different type of evidence and assesses its relevance to the rebound effect. Each seeks in particular to clarify the conceptual issues underlying this debate and to make these issues as accessible as possible to a non-technical audience.

The aim of this shorter *Supplementary Note* is to provide a graphical analysis of rebound effects and in particular to clarify the distinction between income/output effects and substitution effects. This permits a clearer understanding of how rebound effects operate.

Each of these reports is available to download from the UKERC website.

THE UK ENERGY RESEARCH CENTRE

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The Centre takes a whole systems approach to energy research, incorporating economics, engineering and the physical, environmental and social sciences while developing and maintaining the means to enable cohesive research in energy.

To achieve this we have developed the Energy Research Atlas, a comprehensive database of energy research, development and demonstration competences in the UK. We also act as the portal for the UK energy research community to and from both UK stakeholders and the international energy research community.

Contents

1 Introduction

The aim of this *Supplementary Note* is to provide a graphical analysis of rebound effects and in particular to clarify the distinction between income and substitution effects for consumers and output and substitution effects for producers. This permits a clearer understanding of how rebound effects operate. The analysis draws upon standard neoclassical theory and is informed in particular by the insightful discussions of the rebound effect by Berkhout *et al* (2000) and Binswanger (2001).

The *rebound effect* is an umbrella term for a number of mechanisms which reduce the size of the 'energy savings' achieved from improvements in energy efficiency. *Direct rebound effects* relate to individual energy services, such as heating and lighting, and are confined to the energy required to provide that service. *Indirect rebound effects* relate to the energy required to provide other goods and services, the consumption of which is affected by the energy efficiency improvement. The *economy-wide rebound effect* represents the sum of direct and indirect rebound effects and is normally expressed as a percentage of the *expected* energy savings from an energy efficiency improvement. Hence, a rebound effect of 100% means that the expected energy savings are entirely offset, leading to zero net savings. The mechanisms that underlie these effects are described in detail in the main report.

For energy efficiency improvements by consumers, it is helpful to decompose the direct rebound effect into:

- a *substitution effect*, whereby consumption of the (cheaper) energy service substitutes for the consumption of other goods and services while maintaining a constant level of 'utility', or consumer satisfaction; and
- an *income effect*, whereby the increase in real income achieved by the energy efficiency improvement allows a higher level of utility to be achieved by increasing consumption of all goods and services, including the energy service.

Similarly, the direct rebound effect for producers may be decomposed into:

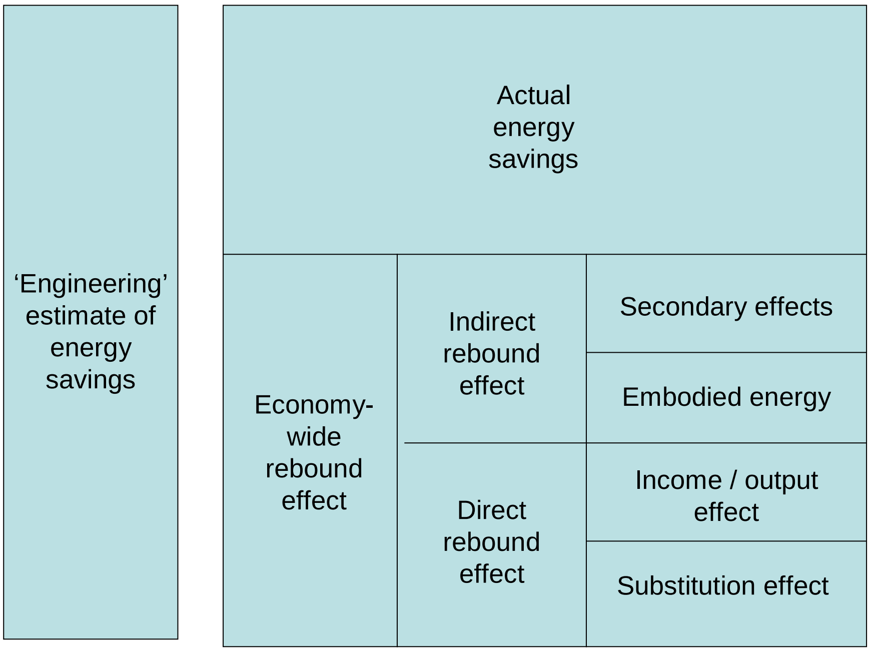
- a *substitution effect*, whereby the cheaper energy service substitutes for the use of capital, labour and materials in producing a constant level of output; and
- an *output effect*, whereby the cost savings from the energy efficiency improvement allows a higher level of output to be produced - thereby increasing consumption of all inputs, including the energy service.

It is also helpful to classify the various mechanisms responsible for indirect rebound effects into two groups:

- the *embodied energy*, or indirect energy consumption required to achieve the energy efficiency improvement, such as the energy required to produce and install thermal insulation; and
- the *secondary effects* that result as a consequence of the energy efficiency improvement, such as the energy associated with increased consumption of other goods and services.

A diagrammatic representation of this classification scheme is provided below. The relative size of each effect may vary widely from one circumstance to another and in some cases individual components of the rebound effect may be negative. It is theoretically possible for the economy-wide rebound effect to be negative ('super conservation'), although in practice this appears unlikely.

Figure 1.1 Classification of rebound effects



The following sections use simple graphical techniques to clarify these distinctions further. Section 2 discusses the direct rebound effects for consumers, Section 3 discusses the indirect rebound effect for consumers and Section 4 discusses the direct rebound effect for producers.

2 The direct rebound effect for consumers

The direct rebound effect for consumers may be illustrated in a simple neoclassical framework, where consumers are assumed to be fully informed and perfectly rational and therefore act to maximise their utility. Utility is assumed to be derived from the consumption of goods and services, including energy services (*ES*) such as thermal comfort, refrigeration and motive power. Energy services are delivered through a combination of energy commodities (*E*) and the associated energy systems, including energy conversion devices. Consumers are assumed to derive utility from consuming energy services, rather than from consuming energy commodities directly. In practice, nearly all services require energy in some form, although energy may form a much smaller proportion of total costs for some services than for others.

An essential feature of an energy service is the *useful work* (*S*) obtained, which may be measured by a variety of thermodynamic or physical indicators (Patterson, 1996).[1] For example, the useful work from passenger vehicles may be measured in vehicle kilometres or passenger kilometres. But energy services also have broader *attributes* (*A*) that may be combined with useful work in a variety of ways. For example, all cars deliver passenger kilometres, but they may vary widely in terms of features such as speed, comfort, acceleration and prestige. The combination of useful work (*S*) with these associated attributes (*A*) may be considered to provide the full energy service: $ES = es(S, A)$.

The energy efficiency (ε) of the relevant energy system is given by the ratio of useful work output to energy input: $\varepsilon = S / E$. The *energy cost* of useful work (P_S) is then given by $P_S = P_E / \varepsilon$, where P_E represents the unit price of energy. This is one component of the *generalised cost* of useful work (P_G), which also includes other costs, such as annualised capital costs, maintenance costs and time costs. Improvements in energy efficiency reduce the energy cost of useful work, but may also affect other costs. In what follows, these other costs are assumed to be unchanged, together with the attributes (*A*) of the energy service.

An improvement in the energy efficiency of the system leads to a reduction in the energy cost of useful work (P_S) and hence the effective price of useful work. As a result, the consumption of useful work may be expected to increase. The response to this price reduction may be illustrated graphically, using *indifference curves*, which represent different combinations of goods/services to which a consumer is *indifferent.* At each point on an indifference curve, a consumer has no preference for one combination of goods over another, so that each point provides the same level of *utility,* or satisfaction. The analysis rests upon a number of standard simplifying assumptions regarding indifference curves and consumer behaviour, including completeness, transitivity, non-satiation, continuity and strict convexity (Gravelle and Rees, 2004).

2.1 Illustration of the direct rebound effect for consumers

In Figure 2.1, the curves U_1 and U_2 represent indifference curves between the consumption of useful work for a particular energy service (*S*) and the consumption of another good or service (*Z*). As an illustration, the useful work may be passenger kilometres in a private

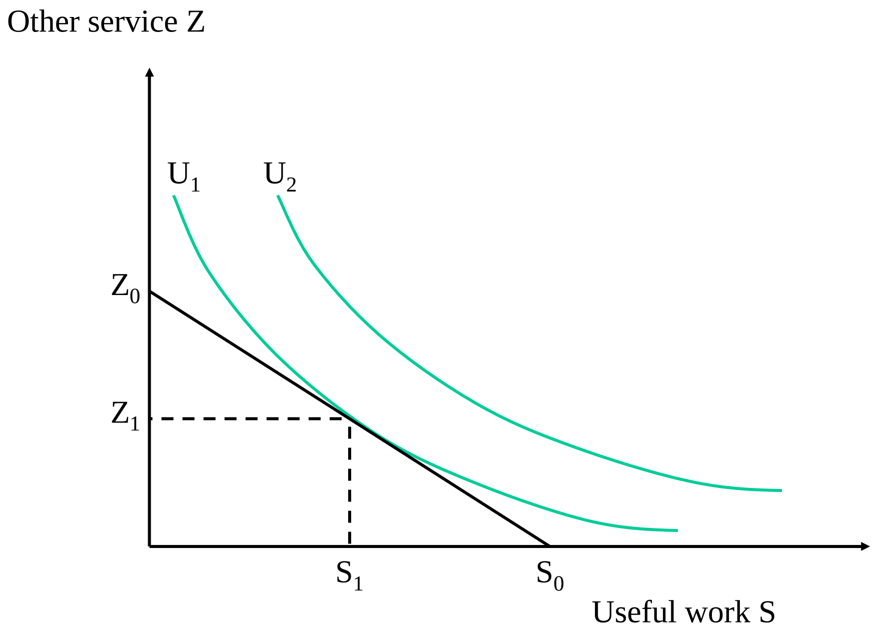
[1] See Technical Report 5 for a comprehensive discussion of thermodynamic, physical and economic measures of energy and energy efficiency, including a definition of output energy or 'useful work'.

automobile, while the other service may be restaurant meals. For illustrative purposes, the consumer is initially assumed to spend all of her income (*Y*) on *S* and *Z* and the non-energy costs of the energy service are assumed to be zero.

The line S_0-Z_0 represents the consumer's budget constraint (*Y*). If P_S represents the energy cost of a unit of useful work and P_Z represents the unit price of the other service, the budget constraint may be written as $Y \geq P_S S_o + P_Z Z_o$. The slope of the budget curve is therefore equal to (P_S/P_Z).

At one extreme, the consumer could choose to consume S_0 useful work and none of the other service, while at the other extreme she could consume Z_0 of the other service and no useful work. The optimum consumption mix is given by (S_1, Z_1), where the budget constraint is tangential to the indifference curve U_1. At this point, utility is maximised and the *marginal rate of technical substitution*[2] between *S* and *Z* is equal to the ratio of their prices (P_S/P_Z).

Figure 2.1 Trade-off between the consumption of useful work S and the consumption of another service Z



Let *E(s)* represent the energy consumption associated with consuming a quantity *s* of useful work (*E(y)>E(x) for y>x*). Then the initial level of energy consumption is given by $E(S_1)$. Now suppose that there is an exogenous improvement in the energy efficiency of delivering this energy service. For example, suppose there is an improvement in the fuel efficiency of the vehicle. For simplicity, we ignore the costs associated with this technical improvement and assume that the attributes of the energy service are otherwise unchanged. The new energy consumption associated with consuming an amount of useful work *S* is given by

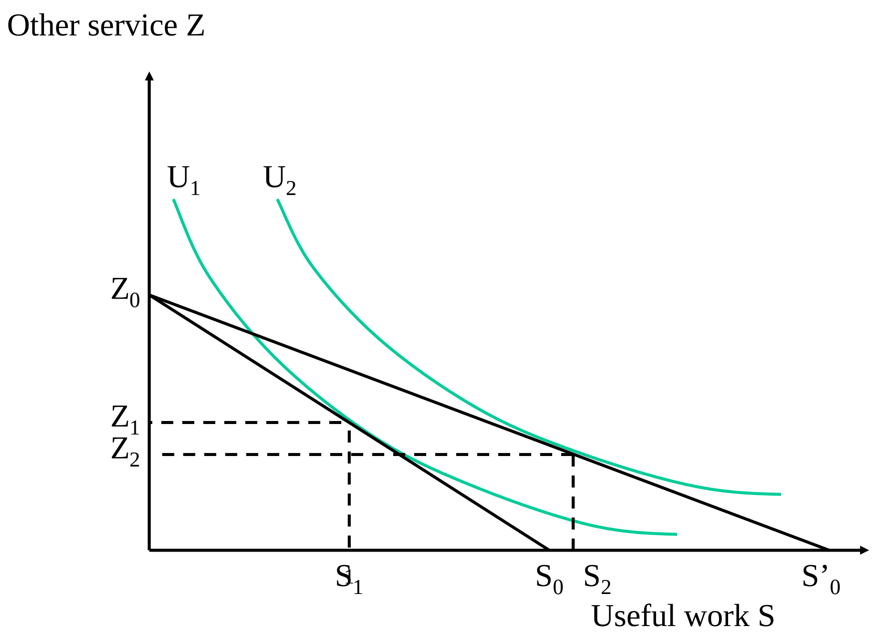
[2] This measures the rate at which one service can be substituted for another while holding utility constant. It is a measure of the slope of the indifference curve: $\left.\frac{\partial Z}{\partial S}\right|_{dU=0} = -\frac{P_z}{P_s}$

$E^*(S)$ (where $E^*(S)<E(S)$). An 'engineering' calculation of the percentage energy savings associated with this fuel efficiency improvement (*ENG*) would then be:

$$ENG = \frac{E(S_1) - E^*(S_1)}{E(S_1)} * 100\% \qquad (2.1)$$

However, this overestimates the actual energy savings because it assumes that the consumption of useful work (*S*) is unchanged following the energy efficiency improvement. If the nominal prices of energy commodities are unchanged, the energy efficiency improvement will reduce the effective price of useful work ($P'_S < P_S$) and therefore increase both consumption of useful work and overall utility. As shown in Figure 2.2, if the consumer were to spend her entire budget on useful work, she would be able to consume a larger quantity S'_0. This may be represented by a shift of the budget line from Z_o-S_o to Z_o-S'_o. In conventional terminology, the consumers 'real income' has increased even though her nominal (money) income is unchanged. The optimum consumption mix is now given by (S_2, Z_2) where the new budget constraint is tangential to the indifference curve U_2 - which represents the maximum amount of utility that can be obtained from the new level of real income. Hence, consumption of useful work has increased ($S_2>S_1$), consumption of the other service has reduced ($Z_2<Z_1$) and the consumer obtains a higher level of utility ($U_2>U_1$).

Figure 2.2 Change in consumption following an improvement in energy efficiency



The actual percentage saving in energy consumption (*ACT*) is then given by:

$$ACT = \frac{E(S_1) - E^*(S_2)}{E(S_1)} * 100\% \qquad (2.2)$$

Since $E^*(S_2) > E^*(S_1)$:

$ACT \leq ENG$

While energy consumption per unit of useful work has *reduced* $(\frac{E^*(S)}{E(S)} < 1)$, the consumption of useful work has *increased* $(S_2 > S_1)$. These two effects offset one another, with the result that the sign of ACT is ambiguous: the technical improvement in energy efficiency may either increase or decrease energy consumption for the energy service.

The direct rebound effect for the individual energy service (REB_d) may then be defined as:

$$REB_d = \frac{ENG - ACT}{ENG} * 100\% \tag{2.3}$$

Hence, if the actual savings equal the estimated savings the direct rebound effect is zero, while if the actual savings are zero the direct rebound effect is 100%. If (as is possible) there is an increase in energy consumption $(ACT < 0)$, the direct rebound effect is >100% - a situation termed 'backfire' in the literature. Substituting, we have:

$$REB_d = \frac{\left(E(S_1) - E^*(S_1)\right) - \left(E(S_1) - E^*(S_2)\right)}{E(S_1) - E^*(S_1)} * 100\% \tag{2.4}$$

Or:

$$REB_d = \frac{E^*(S_2) - E^*(S_1)}{E(S_1) - E^*(S_1)} * 100\% \tag{2.5}$$

2.2 Decomposing the direct rebound effect for consumers

A key determinant of the direct rebound effect is the responsiveness of the demand for useful work to changes the energy cost of useful work (P_S), holding income, the price of other goods and preferences constant. This 'own price elasticity' is defined as:

$$\eta_{P_S}(S) = \frac{\partial S}{\partial P_S} \frac{P_S}{S} \tag{2.6}$$

A higher (lower) elasticity leads to a greater (smaller) change in the quantity demanded in response to a change in price. Conventionally, demand for useful work is said to be elastic when $\left|\eta_{P_S}(S)\right| \geq 1$ and inelastic when $\left|\eta_{P_S}(S)\right| \leq 1$. The own-price elasticity of useful work will be determined in part by the availability of substitutes for the relevant energy service. For example, the elasticity of demand for car travel may be expected to be higher if public transport alternatives are available. The elasticity will also depend upon the time frame under consideration and should be higher in the long-run since consumers have more time to adjust. While short-run changes in demand result largely from changes in equipment utilisation, in the long run equipment will be replaced and there may be changes in the number, capacity and characteristics of that equipment.

Following standard practice in microeconomics, the own price elasticity of useful work may be decomposed into a *substitution* effect and an *income* effect (Varian, 1996):

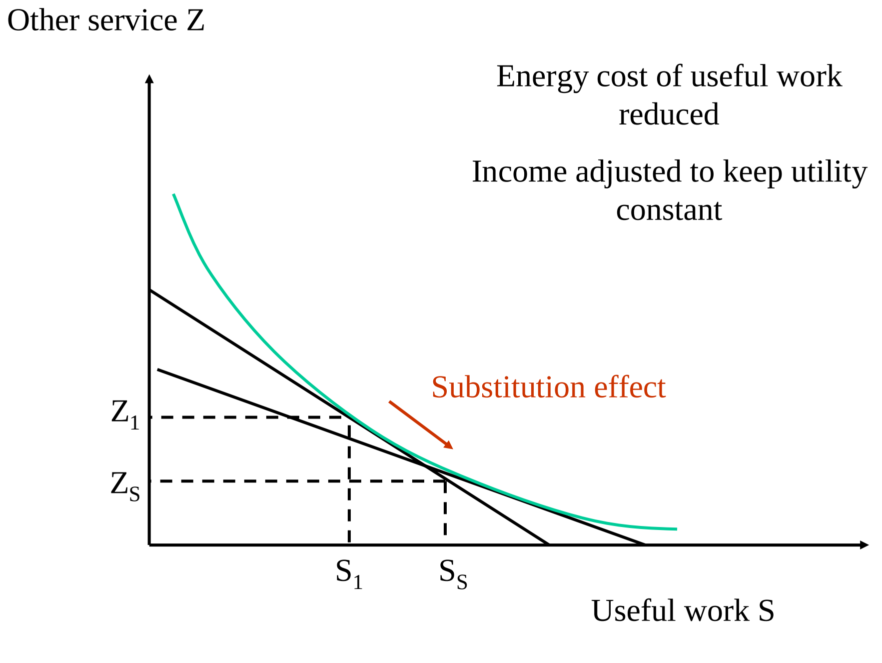
- *Substitution effect*: A decrease in the price of supplying useful work means that the rate at which the consumer can exchange consumption of useful work for consumption of other goods and services has increased. As a result, increased consumption of useful work will substitute for reduced consumption of other goods and services. The substitution effect is defined as the change in consumption that would result from the change in relative prices *if* income were adjusted to keep utility constant. In effect, the change in consumption is artificially restricted to a movement along the original indifference curve.

- *Income effect:* Since useful work has become cheaper, the consumer's total purchasing power, or 'real income' has increased. This allows a shift from one indifference curve to another. The income effect may be defined as the change in consumption that would result exclusively from this change in real income, holding other prices and money income constant.

This decomposition is theoretical, in that only the sum of the two effects can be empirically observed, but is helpful in understanding the nature of the price response.

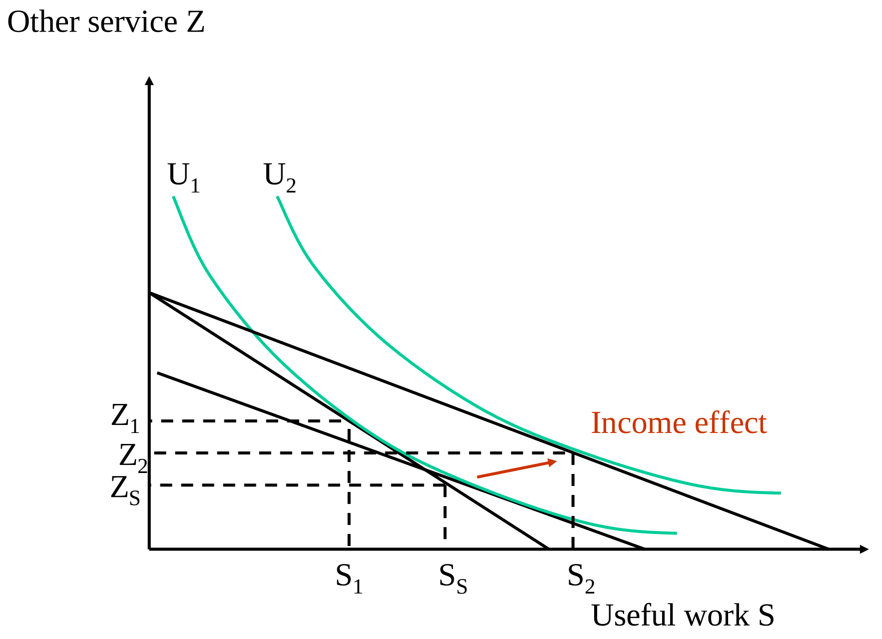
The substitution effect is illustrated in Figure 2.3. Here, the slope of the budget constraint has changed as result of the change in relative prices, but its location is artificially constrained to allow utility (U_1) to be unchanged. The consumption of useful work increases from S_1 to S_S, while the consumption of the other service decreases from Z_1 to Z_S.

Figure 2.3 Substitution effect following a decrease in the energy cost of useful work



The income effect is illustrated in Figure 2.4. Here, the budget constraint is shifted rightwards to reflect the increase in real income. The consumption of useful work increases from S_S (substitution effect alone) to S_2 (substitution effect + income effect = total effect). Also, the consumption of the other service increases from Z_S to Z_2 and utility increases from U_1 to U_2.

Figure 2.4 Income effect following a decrease in the energy cost of useful work



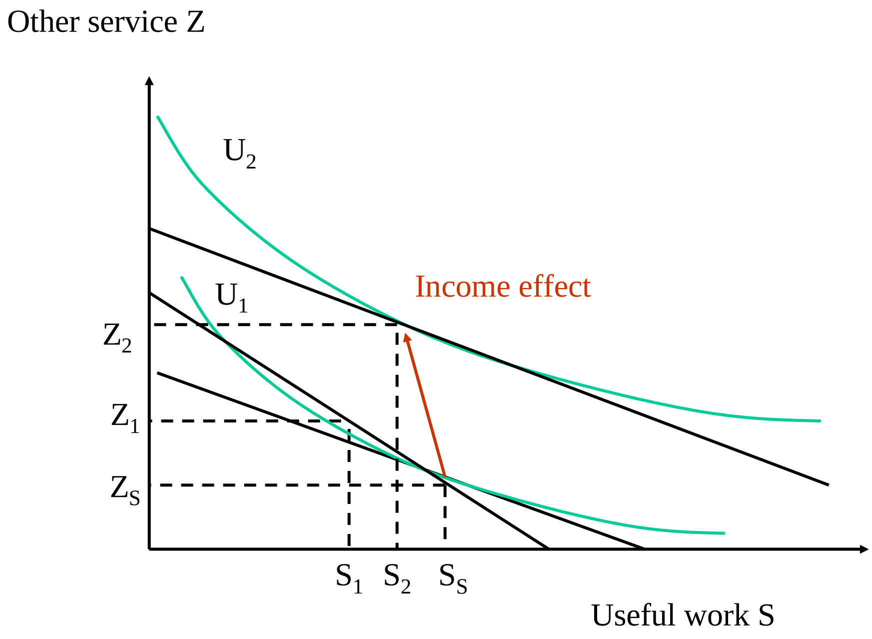
The substitution effect will always lead to an increase in consumption of useful work following an improvement in energy efficiency. The magnitude will depend upon the degree of substitutability between useful work and the other service and may be close to zero if there is limited substitutability. In contrast, the income effect may either increase or decrease consumption of useful work, depending upon whether useful work for this energy service is a 'normal' good or an 'inferior' good (Binswanger, 2001). Demand for a normal good (or service) will increase following an increase in real income, while demand for an inferior good will decrease. For example, it is possible that bus travel is an inferior good, since demand may decline above a certain level of income.

The consequence of the income effect when useful work for this energy service is an inferior good is illustrated in Figure 2.5. Here, the income effect leads to a reduction in the consumption of useful work from S_S to S_2. However, this is not sufficient to counteract the substitution effect, so there is still a net increase in the consumption of useful work from S_1 to S_2. In this case, the final demand for the other service *increases* from Z_1 to Z_2.

It is theoretically possible for the negative income effect for an inferior energy service to outweigh the substitution effect. In this case, the decrease the energy cost of useful work following the energy efficiency improvement will lead to a net *decrease* in demand for useful work.[3] In practice, however, this appears unlikely.

[3] The inferior energy service would be termed a 'Giffen good' in this instance (Varian, 1996).

Figure 2.5 Income effect when useful work is an inferior good



This decomposition into a substitution and an income effect has been formalised in the 'Slutsky equation' (Varian, 1996). This states that the price elasticity of demand for a good is equal to the price elasticity at constant utility (or 'compensated' demand) minus the product of the income elasticity of demand and the share of the good in the overall budget:

Total effect = substitution effect - income effect

$$\eta_{P_S}(S) = \eta^C_{P_S}(S) - \eta_Y(S)\left(\frac{P_S S}{Y}\right)$$

$$\eta_{P_S}(S) = \eta^C_{P_S}(S) - \eta_Y(S) * C_S \qquad (2.7)$$

Where:

$\eta_{P_S}(S)$	=	own-price elasticity of demand for useful work
$\eta^C_{P_S}(S)$	=	income compensated (i.e. constant utility) own-price elasticity of demand
$\eta_Y(S)$	=	income elasticity of demand for useful work
Y	=	total expenditure
C_S	=	share of useful work in total expenditure

The substitution effect is negative, because an increase (decrease) in the price of a good leads to a decrease (increase) in demand. The income effect for a normal good is positive because an increase (decrease) in real income leads to an increase (decrease) in demand. In contrast, the income effect for an inferior good is positive. With a normal good, the substitution and income effects reinforce one another, while with an inferior good they counteract one another. The substitution effect is larger when useful work (*S*) is a good substitute for the other good/service (*Z*), while the income effect is larger when useful work accounts for a larger share of the overall budget.

3 The indirect rebound effect for consumers

The above analysis is confined to a situation where the consumer chooses between only two goods/services – S and Z. In practice, a change in the energy cost of useful work will change the demand for multiple goods and services (Z_k). Consumption of some of these goods and services may decrease following the energy efficiency improvement, while the consumption of others may increase. If the former is the case, then S and Z_i are said to be *substitutes*, while if the latter is the case then S and Z_i are said to be *complements*.

Since these other goods and services will generally require energy for their provision, an improvement in energy efficiency will have an *indirect* effect on aggregate energy consumption that is additional to its direct effect. For example, the savings from lower heating bills may be put towards an overseas holiday.

A key determinant of the indirect rebound effect is the proportional change in the consumption of the other good/service (Z) following a proportional change in the energy cost of useful work (P_S), holding income and other prices constant. This 'cross price elasticity' is defined as:

$$\eta_{P_S}(Z) = \frac{\partial Z}{\partial P_S}\frac{P_S}{Z} \qquad (3.1)$$

A higher (lower) elasticity leads to a greater (smaller) change in demand in response to a change in price. Conventionally, goods/services are said to be *substitutes* if the cross price elasticity is positive and *complements* if the cross price elasticity is negative. For example, public transport is a direct substitute for travel by car travel, while restaurant meals are not. Hence, the cross price elasticity for the former may be expected to be higher than that for the latter.

Let *E(z)* represent the energy consumption associated with consuming *z* amount of a particular service Z_k (e.g. restaurant meals). Then the indirect change in energy consumption associated with service Z_k following the energy efficiency improvement is given by:

$$IND = E(Z_{k1}) - E(Z_{k2}) \qquad (3.2)$$

As with the direct change in energy consumption, the indirect change in energy consumption following the energy efficiency improvement may be either positive or negative. However, unlike the direct change, the sign of the indirect change depends solely upon whether the demand for Z either increases or decreases. The energy intensity of Z_k is assumed to remain unchanged.

The total rebound effect, taking into account both the direct change in energy consumption for the energy service and the indirect change in energy consumption for the other service (REB_{id}) is then given by:

$$REB_{id} = \frac{\left(E(S_1) - E^*(S_1)\right) - \left[\left(E(S_1) - E^*(S_2)\right) + \left(E(Z_{k2}) - E(Z_{k1})\right)\right]}{E(S_1) - E^*(S_1)} * 100\% \qquad (3.3)$$

$$REB_{id} = \frac{\left(E^*(S_2) - E^*(S_1)\right) + \left(E(Z_{k2}) - E(Z_{k1})\right)}{E(S_1) - E^*(S_1)} * 100\% \qquad (3.4)$$

Compared to the equation for the direct rebound effect derived earlier, there is an additional term in the numerator. If $E(Z_{k2}) > E(Z_{k1})$, the energy savings from the energy efficiency improvement will be reduced and the direct + indirect rebound effect will be larger than the direct effect. Conversely, if $E(Z_{k2}) < E(Z_{k1})$, the energy savings from the energy efficiency improvement will be increased and the direct + indirect rebound effect will be smaller than the direct effect.

The direct rebound effect will be enhanced by the indirect rebound effect if demand for Z_k increases ($Z_{k2} > Z_{k1}$), while the direct rebound effect will be offset by the indirect rebound effect if demand for Z decreases ($Z_{k2} < Z_{k1}$) .Since the demand for Z_k will always decrease as a result of the substitution effect, the only circumstances in which demand for Z_k will increase is where the income effect is sufficient to offset the substitution effect for Z_k.

Improvements in the energy efficiency of delivering a particular energy service may be expected to influence the demand for a host of other goods and services. If there are K services in total, the rebound effect taking into account both the direct change in energy consumption for energy service S and the indirect change in energy consumption for all the other services Z_k (REB_{id}) is then given by:

$$REB_{id} = \frac{\left(E^*(S_2) - E^*(S_1)\right) + \left(\sum_{k=1,K} E(Z_{k2}) - E(Z_{k1})\right)}{E(S_1) - E^*(S_1)} * 100\% \qquad (3.5)$$

For each individual service Z_k, the change in demand (Z_{k2}-Z_{k1}) will be determined by the cross price elasticity, while the indirect change in energy consumption will be determined by the combination of the cross price elasticity and the corresponding energy intensity ($E(Z)$). Data on these variables may be difficult to obtain, even for relatively aggregate categories of goods and services (k) and is likely to vary from one circumstance to another. As a result, the aggregate rebound effect is specific to individual situations and is likely to be very difficult to estimate empirically.

4 The direct rebound effect for producers

The direct rebound effect for producers may be also illustrated in a simple neoclassical framework. There are many similarities to the analysis of the direct rebound effect for consumers but, as explained below, the analogy is not exact.

Here, we initially examine the situation of a producer in a competitive product market. The producer is assumed to be fully informed and perfectly rational and to choose input combinations and output levels so as to maximise profits. For simplicity of exposition, there are assumed to be only two factors of production: *useful work* (provided through a combination of energy commodities and associated energy conversion equipment) and *capital*. As before, the response to a reduction in the effective price of useful work may be illustrated graphically.

Note that this differs from the conventional approach where *energy* is taken as the factor of production. The differences between the two approaches are also illustrated below. In practice, a multi-input production function would be appropriate, involving trade-offs between capital, energy, labour and material inputs. This complicates the analysis, and is not necessary for the purpose of illustration.[4]

4.1 Illustration of the direct rebound effect for producers

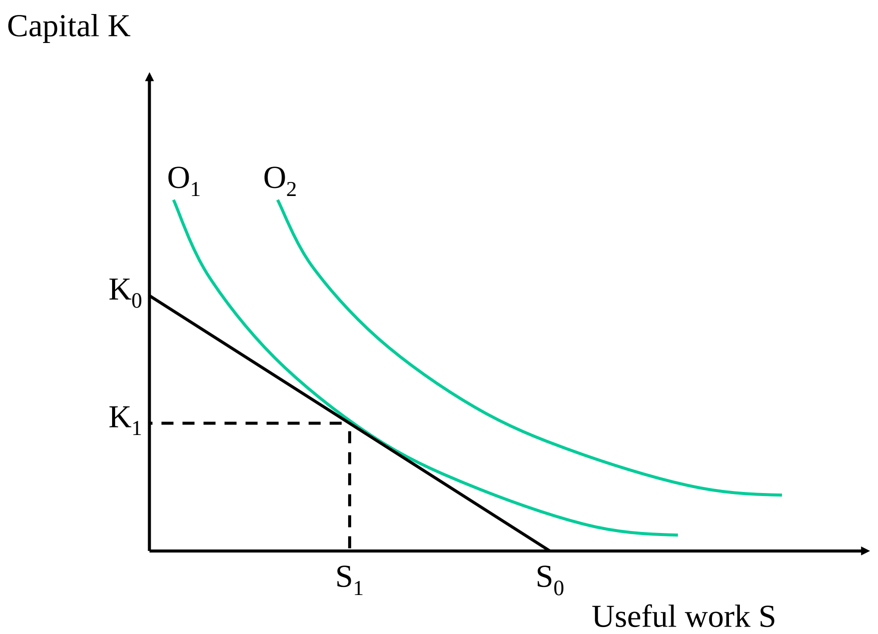
In Figure 4.1, the curves O_1 and O_2 are termed 'isoquants' and represent all the possible combinations of a particular type of capital (*K*) (e.g. chemical processes) and a particular type of useful work (*S*) (e.g. high-pressure steam) capable of producing a given level of output (*O*). It is assumed that the inputs are continuously variable and substitutable over the range shown although in practice the degree of substitutability may be very limited in the short term. Over the long-term, all factor inputs are variable, although the scope for substitution may nevertheless be constrained.

The line S_0-K_0 is termed an isocost line for the two inputs *K* and *S*. If P_S represents the unit cost of useful work *S* and P_K represents the unit cost of capital *K*, the total cost *C* of using a quantity *k* of capital and *s* of useful works is $C = P_K k + P_S s$. The isocost line has a slope equal to $-P_S/P_K$ and may be written: $k = C / P_K - (P_S / P_K)s$. The optimum mix of *K* and *L* is given by (S_1, K_1), where the isocost line is tangential to the isoquant Q_1. At this point, output is maximised for given expenditure and the 'marginal rate of technical substitution' between *K* and *S* is equal to the ratio of their prices.[5]

[4] See Technical Report 4 for a comprehensive discussion of multi input production functions and associated elasticities of substitution.

[5] $\left.\frac{\partial K}{\partial S}\right|_{dQ=o} = -\frac{P_K}{P_S}$

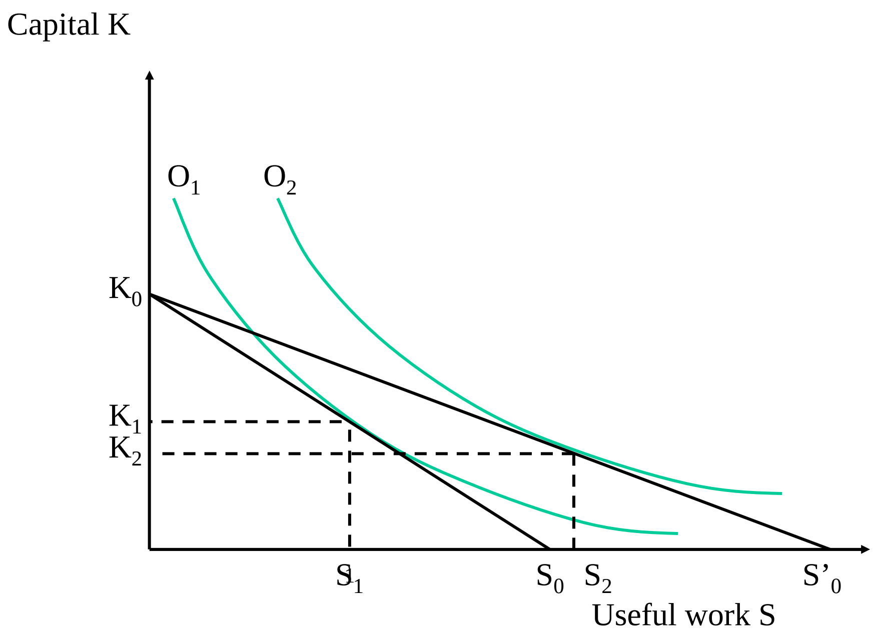
Figure 4.1 Trade-off between capital (K) and useful work (S) in the production of a good



As before, let *E(s)* represent the energy consumption associated with consuming a quantity *s* of useful work *S*. The initial energy consumption is then $E(S_1)$. Now suppose that there is an exogenous improvement in the energy efficiency of delivering this energy service. Again, ignore the costs associated with this technical improvement and assume that the attributes of the energy service are otherwise unchanged. Let *E*(s)* represent the new energy consumption associated with consuming a quantity *s* of useful work.

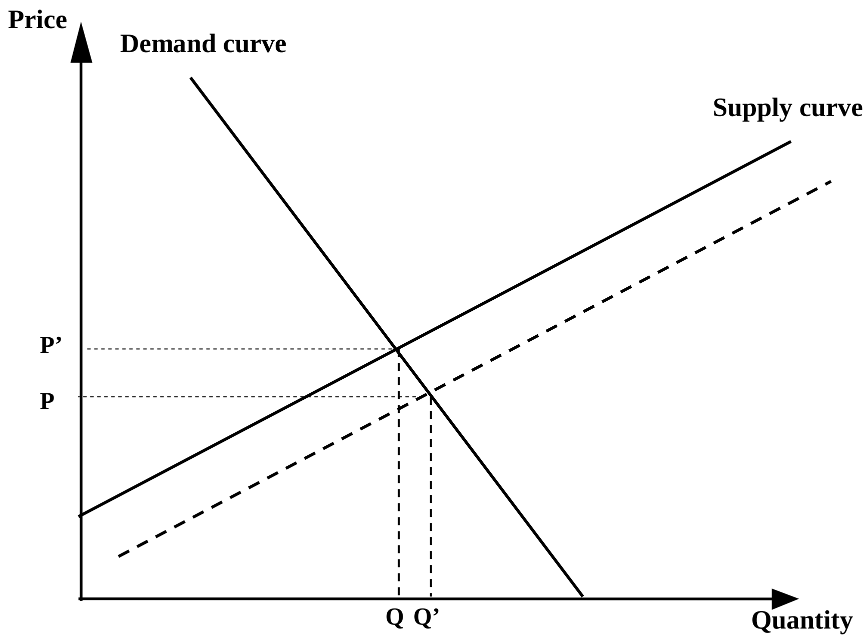
If the nominal prices of energy commodities are unchanged, the energy efficiency improvement will reduce the effective price of delivering useful work ($P'_S < P_S$). In Figure 4.2, this is represented by a shift of the isocost line to K_o-S'_o. The optimal input mix *if the total expenditure on inputs is fixed at C* is now given by (K_2, S_2). A shift to (K_2, S_2) leads to an increase in consumption of useful work $(S_2>S_1)$, a reduction in the use of capital $(K_2<K_1)$ and the production of a higher level of output $(O_2>O_1)$.

Figure 4.2 Initial change in input mix and product output following an improvement in energy efficiency



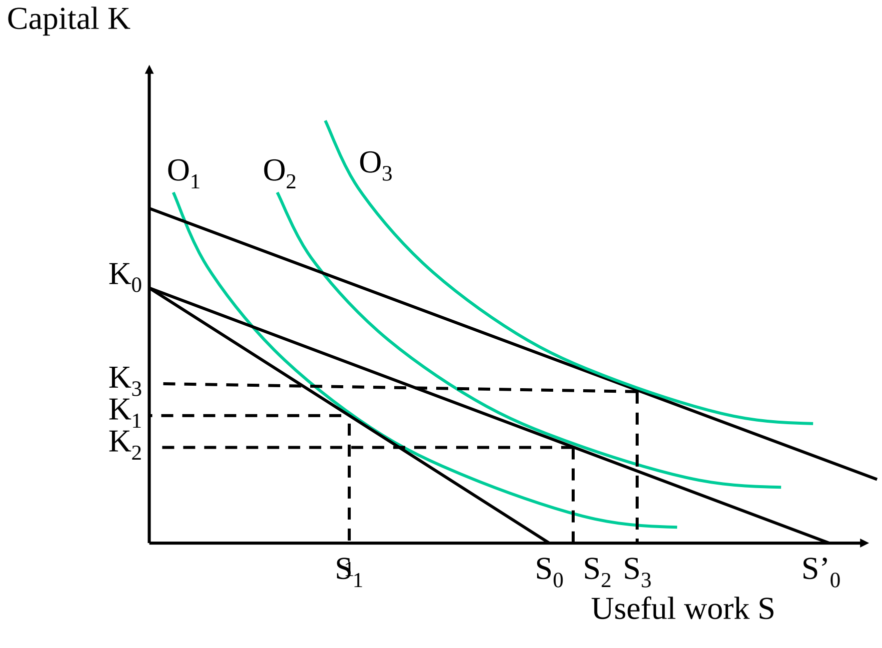
However, (in contrast to the consumer) the adjustments by the individual firm may not stop there. To the firm, the equilibrium represented by (*S2, K2*) is only optimal in the sense that the input combination is appropriate to the level of expenditure on inputs represented by $C = P_K k + P_S s$. But the objective of the firm is not to maximise output (*Q*) subject to a constraint on total input costs (*C*), but instead to maximise profits. The energy efficiency improvement will enable the producer to produce the same output at a lower price. In a perfect market, a price war will develop, leading (in the long term) to a reduction in the long-term average cost of production. The aggregate supply curve for the product will shift to the right, commodity prices will fall and quantities demanded and supplied will increase (Figure 4.3).

Figure 4.3 Aggregate increase in supply following energy efficiency improvements



Hence, for the individual producer, output may be expected to increase further, from O_2 to O_3 in Figure 4.4. This further *profit maximising* adjustment gives a final equilibrium represented by point (K_3, S_3).

Figure 4.4 'Profit maximising' change in input mix and product output following an improvement in energy efficiency



The increased consumption of useful works will offset the potential reduction in energy consumption from the energy efficiency improvement. In a similar way to the previous section, the direct rebound effect for the individual producer can be shown to be:

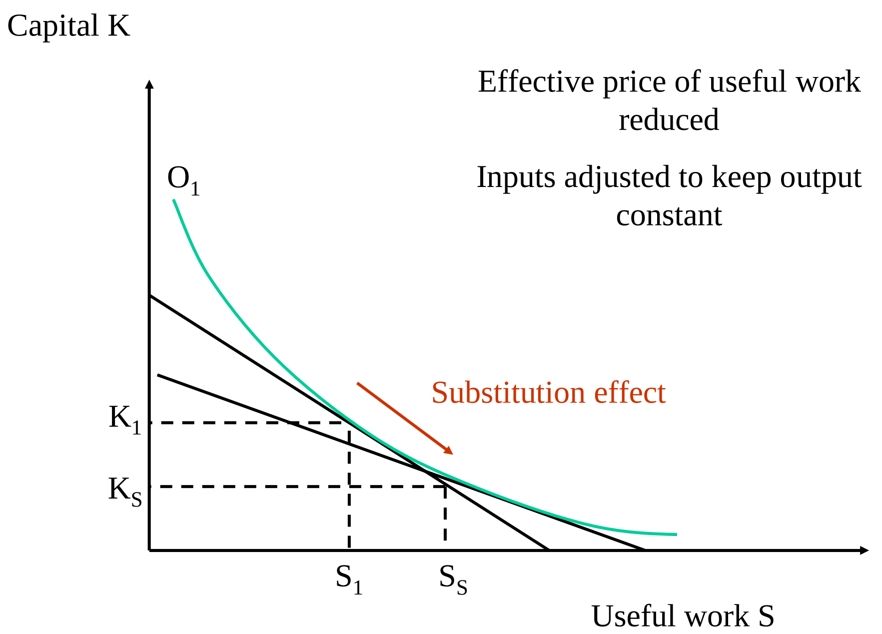
$$REB_d = \frac{E^*(S_3) - E^*(S_1)}{E(S_1) - E^*(S_1)} * 100\% \qquad (4.1)$$

4.2 Decomposing the direct rebound effect for producers

The response of the producer to the energy efficiency improvement *keeping expenditure on inputs fixed* can be decomposed into a *substitution* and *output* effect in an analogous manner to the decomposition for consumers. However, as indicated above, the additional profit maximising effect must also be taken into account.

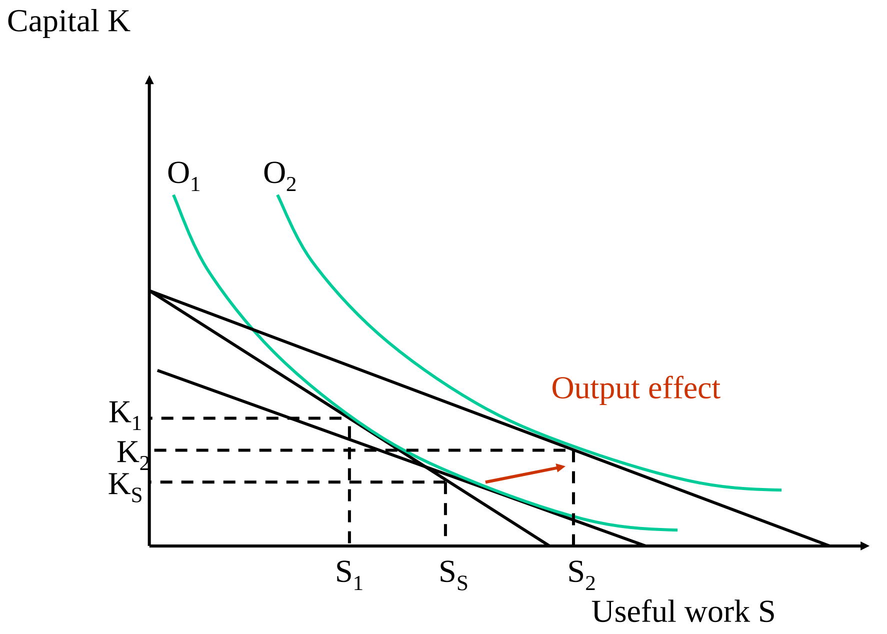
The substitution effect is shown in Figure 4.5. It is defined as the change in input mix that would result from the change in relative prices *if* output were fixed at O_1. Consumption of useful work increases from S_1 to S_S, while the consumption of capital decreases from K_1 to K_S.

Figure 4.5 The substitution effect for producers



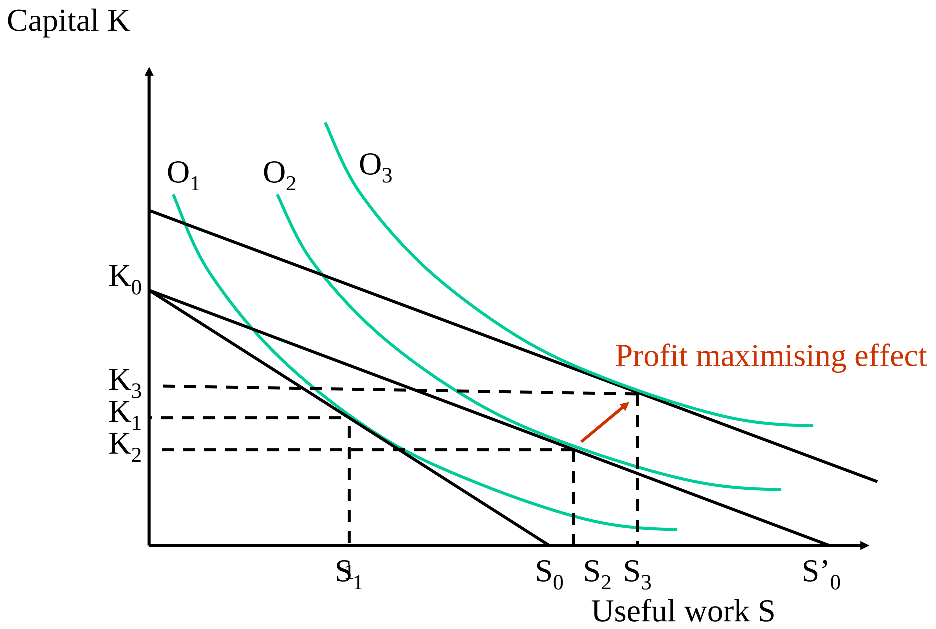
The output effect (Figure 4.6) follows in a similar fashion to the income effect. Here, the isocost line is shifted rightwards to correspond to the original input expenditures (*C*). The consumption of useful work increases from S_S (substitution effect alone) to S_2 (substitution effect + output effect). Consumption of capital increases from K_S to K_2 and output increases from O_1 to O_2.

Figure 4.6 The output effect for producers



The final profit maximising adjustment is illustrated in Figure 4.7. In the final equilibrium, consumption of both capital (K_3>K_1) and useful work *(S_3>S_1)* has increased.

Figure 4.7 The profit maximising effect for producers



As with consumers, the substitution effect will always increase demand for useful work, while the output and profit maximising effects effect may either increase or decrease demand for useful work, depending upon whether useful work is a 'normal' or 'inferior' factor of production. Demand for a normal factor will increase following an increase in input expenditures (*C*), while demand for an inferior factor will decrease.[6]

If useful work is an inferior factor, the output and profit maximising effects will reduce consumption of useful work. It is an empirical question as to whether this will be sufficient to offset the increase in consumption of useful work from the substitution effect.

Note that the ouput and profit maximising effects are not always distinguished in this way. In many circumstances, the combination of the two is referred to as the output effect. Note further that the analysis is substantially more complicated when multi-input production functions are employed. For example, a decrease in the price of useful work could *increase* the demand for capital, rather than reduce it (Berndt and Wood, 1979). These issues are discussed in detail in *Technical Report 4*.

4.3 An alternative presentation of the direct rebound effect for producers

It is more conventional to develop a production function showing the trade-offs between capital and *energy* inputs, rather than useful work – as shown in Figure 4.8 (Berkhout*, et al.*, 2000). With this approach, a technological improvement in energy efficiency is represented by a shift of the isoquant to the left, from *Y* to *Y'*. Here, *Y'* represents the same level of output as *Y*, but technological improvements have reduced the amount of energy needed to produce this output, for the same capital input.

In Figure 4.8, the initial optimum for a given level of input expenditures is represented by (K_1, E_1). Following the energy efficiency improvement, *if* the amount of capital used were unchanged, the new factor mix would be represented by (K_1, E_2). If this were the case, the reduction in energy consumption would be given by (E_1-E_2). Since the price of energy remains unchanged (unlike the effective price for useful work which has reduced) the same level of output would be produced with a smaller expenditure on inputs.

But the optimal factor mix following the energy efficiency improvement is given by equating the marginal rate of technical substitution between capital and energy to the ratio of their prices (which is unchanged). This new optimum is (K_2, E_3), located where the isocost line is tangential to the new isoquant (Y'). Hence, the producer switches to a more energy intensive factor mix and the reduction in energy consumption from the energy efficiency improvement is only (E_1-E_3).

[6] The expenditure elasticity of a factor *x* is defined as: $\frac{dX}{dC}\frac{C}{X}$, where X is expenditure on factor *x* and *C* is total expenditure on inputs. A factor of production is said to be superior, normal, or inferior according as it is expenditure electricity exceed unity, lies in the unit interval, or is negative.

Figure 4.8 Alternative presentation of the direct rebound effect for the producer

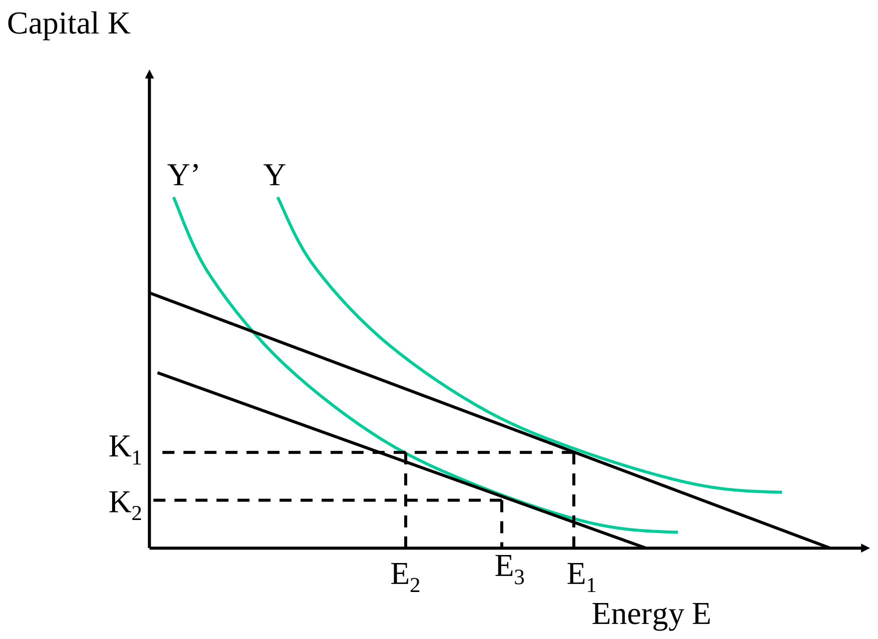
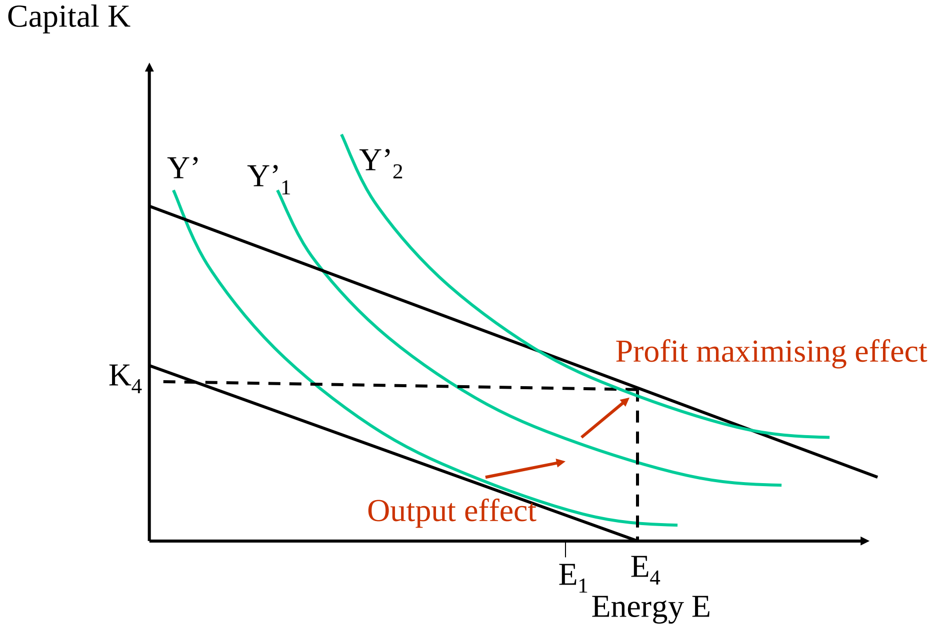


Figure 4.8 represents the direct rebound effect when the output from the producer is unchanged (*Y=Y'*). This is equivalent to the substitution effect described in the previous section. But there is also an *output* effect, since a higher level of output can be produced for a given expenditure on inputs, and a *profit maximising* effect, where output can be increased further to maximise profits. These two effects are illustrated in Figure 14, where Y'_1 and Y'_2 represent higher levels of output. The final optimum is given by (K_4, E_4). The final energy consumption (E_4) may be less than, equal to or greater than the original energy consumption (E_1).

Figure 4.9 Final direct rebound effect for the producer



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