



The Rebound Effect:

an assessment of the evidence for economy-wide energy savings from improved energy efficiency

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The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency

A report produced by the Sussex Energy Group for the Technology and Policy Assessment function of the UK Energy Research Centre

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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 address key controversies in the energy field through comprehensive assessments of the current state of knowledge. It aims to provide authoritative reports that set high standards for rigour and transparency, while explaining results in a way that is both accessible to non-technical readers and useful to policymakers.

This report summarises the main conclusions from 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 and upon the recommendation of the TPA Advisory Group, which is comprised of independent experts from government, academia and the private sector. The assessment addresses the following question:

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

The Summary Report seeks to present the main conclusions of this assessment in a relatively non-technical manner. The results of the full assessment are contained in 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

A shorter *Supplementary Note* provides a graphical analysis of rebound effects. All these reports are available to download from the UKERC website at: www.ukerc.ac.uk

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.

About UKERC

The UK Energy Research Centre's mission is to be the UK's pre-eminent centre of research and source of authoritative information and leadership on sustainable energy systems. It undertakes world-class research addressing the whole-systems aspects of energy supply and use while developing and maintaining the means to enable cohesive research in energy. UKERC is funded by the UK Research Councils.

Acknowledgements

This report has been written by Steve Sorrell (Sussex Energy Group, University of Sussex), but it is based upon the work of the full Project Team, which also includes: John Dimitropoulos (Sussex Energy Group); Lester Hunt and David Broadstock (Surrey Energy Economics Centre, University of Surrey); Grant Allan, Michelle Gilmartin, Peter McGregor, Kim Swales and Karen Turner (Fraser of Allander Institute and Department of Economics, University of Strathclyde); and Matt Sommerville and Dennis Anderson (ICEPT, Imperial College).

John Dimitropoulos played a central role throughout the project, making an invaluable contribution to all aspects of the research. Dennis Anderson provided two insightful papers that greatly improved our understanding of the economy-wide rebound effect. The remaining members of the Project Team co-authored one of the five Technical Reports that provide the foundation for this report (see Annex 2). While aspects of all their work have been incorporated into this report, individual members of the Project Team are not responsible for its contents.

We have benefited enormously during this project from our interactions with Harry Saunders (Decision Processes Inc). We are also grateful for the insightful comments received from our three peer reviewers, namely Manuel Frondel (ZEW), Karsten Neuhoff (University of Cambridge) and Jake Chapman. Valuable comments have also been received from Nick Eyre (Energy Savings Trust), Terry Barker (4CMR), Serban Scriciu (4CMR), Blake Alcott, Len Brookes, John Feather and Gordon Mackerron, as well as from participants at the 29th IAEE International Conference (2006).

We are extremely grateful for the guidance, comments, patience and moral support offered by Jim Skea (UKERC Research Director), Rob Gross (Head of UKERC TPA function), Dennis Anderson (Senior Advisor, UKERC TPA) and Phil Heptonstall (UKERC TPA). Thanks also to Phil for copy editing.

Useful comments and advice have also been received from our Advisory Group, namely: Jim Skea (UKERC); Horace Herring (Open University); Hunter Danskin (DEFRA); Tina Dallman (DEFRA); Ken Double (Energy Saving Trust); Lester Hunt (Surrey Energy Economics Centre); and Paolo Agnolucci (Policy Studies Institute).

This project has tried to summarise the work of hundreds of economists and analysts, many of whom understand these issues much better than ourselves. A particular debt is owed to Lorna Greening and David Greene for their previous synthesis of empirical work in this area (Greening and Greene, 1998).

The above individuals represent a range of views about the size of the economy-wide rebound effect and none of them are responsible for the content of this report.

Executive Summary

Most governments are seeking ways to improve energy efficiency in pursuit of their energy policy goals. The potential 'energy savings' from improved energy efficiency are commonly estimated using basic physical principles and engineering models. However, the energy savings that are realised in practice generally fall short of these engineering estimates. One explanation is that improvements in energy efficiency encourage greater use of the services (for example heat or mobility) which energy helps to provide. Behavioural responses such as these have come to be known as the energy efficiency "rebound effect". While rebound effects vary widely in size, in some cases they may be sufficiently large to lead to an overall **increase** in energy consumption - an outcome that has been termed 'backfire'. There is some evidence to suggest that improvements in the energy efficiency of certain 'pervasive' technologies such as steam engines and electric motors have contributed to backfire in the past.

Rebound effects are very difficult to quantify, and their size and importance under different circumstances is hotly disputed. Also, rebound effects operate through a variety of different mechanisms and lack of clarity about these has led to persistent confusion. In general, rebound effects have been neglected when assessing the potential impact of energy efficiency policies. A key conclusion of this report is that rebound effects are of sufficient importance to merit explicit treatment. Failure to take account of rebound effects could contribute to shortfalls in the achievement of energy and climate policy goals.

This report analyses the nature, operation and importance of rebound effects and provides a comprehensive review of the available evidence on this topic, together with closely related issues, such as the link between energy consumption and economic growth. It assesses the strengths and weaknesses of the evidence base, clarifies the underlying disputes and highlights the implications for energy and climate policy. The key message is that promoting energy efficiency remains an effective way of reducing energy consumption and carbon emissions. But more explicit treatment of rebound effects is needed to assess the contribution that energy efficiency can realistically make.

Defining the rebound effect

- Many energy efficiency improvements do not reduce energy consumption by the amount predicted by simple engineering models. Such improvements make energy services cheaper, so consumption of those services increases. For example, since fuel-efficient vehicles make travel cheaper, consumers may choose to drive further and/or more often, thereby offsetting some of the energy savings achieved. Similarly, if a factory uses energy more efficiently it becomes more profitable encouraging further investment and greater levels of output. This is termed the *direct* rebound effect.
- Even if consumption of energy services remains unchanged, there are reasons why energy savings across the economy may be less than simple calculations suggest. For example, drivers of fuel-efficient cars may spend the money saved buying petrol on other energy-intensive goods and services, such as an overseas flight. Similarly, any

reductions in energy demand will translate into lower energy prices which encourage increased energy consumption. These mechanisms are collectively known as *indirect* rebound effects. The sum of direct and indirect rebound effects represents the *economy-wide* rebound effect. Rebound effects are normally expressed as a percentage of the expected energy savings from an energy efficiency improvement, so a rebound effect of 20% means that only 80% of the expected energy savings are achieved.

- Disputes over the magnitude of rebound effects arise in part from lack of clarity about definitions. Energy efficiency can be measured in a variety of ways, for example using physical indicators (tonnes of coal per tonne of steel) or economic ones (energy per unit of output measured in £). Energy efficiency can also be measured at different levels, for example for an individual manufacturing process, a factory, a company, a sector or even the economy as a whole. Estimates of the rebound effect therefore depend upon the indicators chosen and the level of analysis.
- Improvements in energy efficiency are often associated with improvements in the productivity of capital, labour and materials. More efficient use of these other inputs will tend to amplify the rebound effect.

Estimating the rebound effect

- The available evidence for all types of rebound effect is far from comprehensive. The evidence is better for direct effects than for indirect effects, but even this focuses on a small number of consumer energy services, such as home heating and personal transportation, within developed countries. Both direct and indirect effects appear to vary widely between different technologies, sectors and income groups and in most cases they cannot be quantified with much confidence. However the evidence does **not** suggest that improvements in energy efficiency routinely lead to economy-wide increases in energy consumption. At the same time the evidence suggests that economy-wide rebound effects will be at least 10% and often higher. Rebound effects therefore need to be factored into policy assessments.
- For household heating, household cooling and personal automotive transport in developed countries, the direct rebound effect is likely to be less than 30% and may be closer to 10% for transport. Direct rebound effects for these energy services are likely to decline in the future as demand saturates. Improvements in energy efficiency should therefore achieve 70% or more of the reduction in energy consumption projected using engineering principles. However, indirect effects mean that the economy-wide reduction in energy consumption will be less.
- Direct rebound effects are likely to be smaller where energy forms a relatively small proportion of total costs and has little influence on operating decisions. The use of electricity in electronic appliances is a good example. However, these effects have only

been studied over relatively limited time periods. There are also some important uncertainties, for example about the link between direct rebound effects and household income.

- There are very few studies of rebound effects from energy efficiency improvements in developing countries. Rebound effects may be expected to be larger in developing countries where demand for energy services is far from saturated. This is supported by the limited empirical evidence available. In some cases, the direct rebound effect may exceed unity.
- Energy-economic models can be used to estimate indirect and economy-wide rebound effects, but there are few published studies and these have a number of flaws. The results demonstrate that the economy-wide rebound effect varies widely depending upon the sector where the energy efficiency improvement takes place. While little confidence can be placed in the available estimates, several studies suggest that economy-wide rebound effects may frequently exceed 50% (i.e. less than half of the expected energy savings will be achieved). Moreover, these estimates do not take into account the amplifying effect of any associated improvements in the efficiency with which capital, labour or materials is used.

Rebound or backfire?

- The so-called 'Khazzoom-Brookes (K-B) postulate' claims that, if energy prices do not change, cost effective energy efficiency improvements will inevitably increase economy-wide energy consumption above what it would be without those improvements ('backfire'). This provocative claim would have serious implications for energy and climate policy if it were correct. However, the theoretical arguments in favour of the postulate rely upon stylised models that have a number of limitations, such as the assumption that economic resources are allocated efficiently. Similarly, the empirical evidence for the postulate is indirect, suggestive and ambiguous. Since a number of flaws have been found with both the theoretical and empirical evidence, the K-B 'hypothesis' cannot be considered to have been verified. Nevertheless, the arguments and evidence used to defend the postulate deserve more serious attention than they have received to date.
- In developed countries, energy use as conventionally measured has grown more slowly than the economy as a whole. From this, it is generally concluded that technical change has improved the efficiency with which energy is used and thereby helped to 'decouple' energy consumption from economic growth. However once different energy sources are weighted by their relative 'quality' or economic productivity, the coupling between energy consumption and economic growth appears far stronger. Taken together, the evidence reviewed in this report suggests that: a) the scope for substituting other inputs for energy is relatively limited; b) much technical change has historically increased energy intensity; c) energy may play a more important role in

economic growth than is conventionally assumed; and d) economy-wide rebound effects may be larger than is conventionally assumed.

- If improvements in energy efficiency are associated with improvements in the efficiency with which other inputs such as capital, labour and materials are used, then it is quite possible that energy consumption may increase as the K-B postulate suggests. However, since the link between the efficiency with which energy and other inputs is used depends on individual technologies and circumstances, there is no *a priori* reason to believe that 'backfire' is an inevitable outcome in all cases.
- The debate over the K-B postulate would benefit from clearer distinctions between different types of energy efficiency improvement. For example, the K-B postulate seems more likely to hold for improvements associated with pervasive 'general-purpose technologies', particularly when these are adopted by producers rather than final consumers and when the improvements occur at an early stage of development and diffusion. Steam engines provide a good illustration from the 19th-century, while electric motors provide a comparable illustration from the early 20th century. The opportunities offered by these technologies have such significant effects on innovation, productivity and economic growth that economy-wide energy consumption is increased over the long-term. Such technologies are generally taken up enthusiastically by the market and are rarely associated with purposeful public policy.
- In contrast, the K-B postulate seems less likely to hold for dedicated energy efficiency technologies such as thermal insulation, particularly when these are used by consumers or when they play a subsidiary role in economic production. These technologies have smaller effects on productivity and economic growth, with the result that economy-wide energy consumption is likely to be reduced.

Policy implications

1. The potential contribution of energy efficiency policies needs to be reappraised.

- Energy efficiency may be encouraged through policies that raise energy prices, such as carbon taxes, or through non-price policies such as building regulations. Both should continue to play an important role in energy and climate policy. However, many official and independent appraisals of such policies have undoubtedly overstated the contribution of non-price policies to reducing energy consumption and carbon emissions.
- It would be wrong to assume that, in the absence of evidence, rebound effects are so small that they can be disregarded. Under some circumstances (e.g. energy efficient technologies that significantly improve the productivity of energy intensive industries) economy-wide rebound effects may exceed 50% and could potentially increase energy consumption in the long-term. In other circumstances (e.g. energy efficiency

improvements in consumer electronic goods) economy-wide rebound effects are likely to be smaller. But in no circumstances are they likely to be zero.

- Taking rebound effects into account will reduce the apparent effectiveness of energy efficiency policies. However, many energy efficiency opportunities are highly cost-effective and will remain so even when rebound effects are allowed for. Provided market and organisational failures can be overcome, the encouragement of these opportunities should increase real income and contribute to economic growth. They may not, however, reduce energy consumption and carbon emissions by as much as previously assumed.

2. Rebound effects should be taken into account when developing and targeting energy efficiency policy

- Rebound effects vary widely between different technologies, sectors and income groups. While these differences cannot be quantified with much confidence, there should be scope for including estimated effects within policy appraisals and using these estimates to target policies more effectively. Where rebound effects are expected to be large, there may be a greater need for policies that increase energy prices.
- 'Win-win' opportunities that reduce capital and labour costs as well as energy costs may be associated with large rebound effects. Hence, the implications of encouraging these opportunities need to be clearly understood and quantified. It may make more sense to focus policy on 'dedicated' energy efficient technologies, leaving the realisation of wider benefits to the market

3. Rebound effects may be mitigated through carbon/energy pricing – whether implemented through taxation or an emissions trading scheme

- Carbon/energy pricing can reduce direct and indirect rebound effects by ensuring that the cost of energy services remains relatively constant while energy efficiency improves. Carbon/energy pricing needs to increase over time at a rate sufficient to accommodate both income growth and rebound effects, simply to prevent carbon emissions from increasing. It needs to increase more rapidly if emissions are to be reduced.
- Carbon/energy pricing may be insufficient on its own, since it will not overcome the numerous barriers to the innovation and diffusion of low carbon technologies and could have adverse impacts on income distribution and competitiveness. Similarly, policies to address market barriers may be insufficient, since rebound effects could offset much of the energy savings. A policy mix is required.

Glossary

AEEI	Autonomous Energy Efficiency Improvements
AES	Allen-Urswa Elasticity of Substitution
CES	Constant Elasticity of Substitution
CGE	Computable General Equilibrium
CPE	Cross Price Elasticity
DEFRA	Department for the Environment, Food and Rural Affairs
EBPP	Evidence Based Policy and Practice
GDP	Gross Domestic Product
GPT	General Purpose Technologies
GWh	Gigawatt Hour
IAEE	International Association for Energy Economics
IEA	International Energy Agency
K-B	Khazzoom-Brookes
kW	Kilowatt - a measure of power, one thousand W
kWh	Kilowatt hours - a measure of energy, one kW of power provided for one hour
MES	Morishima Elasticity of Substitution
MRTS	Marginal Rate of Technical Substitution
OECD	Organisation for Economic Cooperation and Development
SUV	Sport Utility Vehicle
TFP	Total Factor Productivity
TPA	UKERC Technology and Policy Assessment function
UKERC	UK Energy Research Centre
ZEW	Zentrum für Europäische Wirtschaftsforschung, Mannheim
4CMR	Cambridge Centre for Climate Change Mitigation Research

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1. Introduction

The UKERC Technology and Policy Assessment (TPA) function was set up to address key controversies in the energy field through comprehensive assessments of the current state of knowledge. It aims to provide authoritative reports that set high standards for rigour and transparency, while explaining results in a way that is both accessible to non-technical readers and useful to policymakers. This latest report addresses the following question:

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

1.1 Context and rationale

To achieve reductions in carbon emissions, most governments are seeking ways to improve energy efficiency throughout the economy. It is generally assumed that such improvements will reduce overall energy consumption, at least compared to a scenario in which such improvements are not made. But a range of mechanisms, commonly grouped under the heading of *rebound effects* may reduce the size of the 'energy savings' achieved. Indeed, there is some evidence to suggest that the introduction of certain types of energy efficient technology in the past has contributed to an overall **increase** in energy demand – an outcome that has been termed 'backfire'. This appears to apply in particular to pervasive new technologies, such as steam engines in the 19th century, that raise overall economic productivity as well as improving energy efficiency.

These rebound effects could have far-reaching implications for energy and climate policy, both in the UK and globally. While cost-effective improvements in energy efficiency should improve welfare and benefit the economy, they could in some cases provide an ineffective or even a counterproductive means of tackling climate change. However, it does not necessarily follow that *all* improvements in energy efficiency will increase overall energy consumption or in particular that the improvements induced by policy measures will do so.

The nature, operation and importance of rebound effects are the focus of a long-running dispute within energy economics. On the micro level, the question is whether improvements in the technical efficiency of energy use can be expected to reduce energy consumption by the amount predicted by simple engineering calculations. For example, will a 20% improvement in the fuel efficiency of passenger cars lead to a corresponding 20% reduction in motor-fuel consumption for personal automotive travel? Economic theory suggests that it will not. Since energy efficiency improvements reduce the marginal cost of energy services such as travel, the consumption of those services may be expected to increase. For example, since the cost per mile of driving is cheaper, consumers may choose to drive further and/or more often. This increased consumption of energy services may be expected to offset some of the predicted reduction in energy consumption.

This so-called direct *rebound effect* was first brought to the attention of energy economists by Daniel Khazzoom (1980)

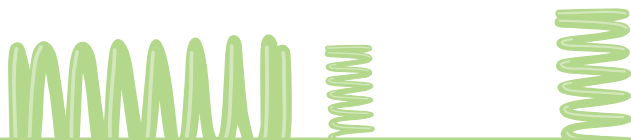
and has since been the focus of much research (Greening, *et al.*, 2000). But even if the direct rebound effect is zero for a particular energy service (e.g. even if consumers choose not to drive any further in their fuel efficient car), there are a number of other reasons why the economy-wide reduction in energy consumption may be less than simple calculations suggest. For example, the money saved on motor-fuel consumption may be spent on other goods and services that also require energy to provide. These so-called *indirect rebound effects* can take

a number of forms that are briefly outlined in Box 1.1. Both direct and indirect rebound effects apply equally to energy efficiency improvements by consumers, such as the purchase of a more fuel efficient car, and energy efficiency improvements by producers, such as the use of energy efficient motors in machine tools.

As shown in Box 1.2, the *overall* or *economy-wide* rebound effect from an energy efficiency improvement represents the sum of these direct and indirect effects. It is normally expressed as a

Box 1.1 Indirect rebound effects

- The equipment used to improve energy efficiency (e.g. thermal insulation) will itself require energy to manufacture and install and this 'embodied' energy consumption will offset some of the energy savings achieved.
- Consumers may use the cost savings from energy efficiency improvements to purchase other goods and services which themselves require energy to provide. For example, the cost savings from a more energy efficient central heating system may be put towards an overseas holiday.
- Producers may use the cost savings from energy efficiency improvements to increase output, thereby increasing consumption of capital, labour and materials inputs which themselves require energy to provide. If the energy efficiency improvements are sector wide, they may lead to lower product prices, increased consumption of the relevant products and further increases in energy consumption.
- Cost-effective energy efficiency improvements will increase the overall productivity of the economy, thereby encouraging economic growth. The increased consumption of goods and services may in turn drive up energy consumption.
- Large-scale reductions in energy demand may translate into lower energy prices which will encourage energy consumption to increase. The reduction in energy prices will also increase real income, thereby encouraging investment and generating an extra stimulus to aggregate output and energy use.
- Both the energy efficiency improvements and the associated reductions in energy prices will reduce the price of energy intensive goods and services to a greater extent than non-energy intensive goods and services, thereby encouraging consumer demand to shift towards the former.



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.¹

Rebound effects need to be defined in relation to particular *time frame* (e.g. short, medium or long term) and *system boundary* (e.g. household, firm, sector, national economy). The economy-wide rebound effect is normally defined in relation to a national economy, but there may also be effects in other countries through changes in trade patterns and international energy prices. Rebound effects may also be expected to increase in importance over time as markets, technology and behaviour adjusts. From a climate change perspective, it is the long-term effect on global energy consumption that is most relevant, but this is also the effect that is hardest to estimate.

The economy-wide rebound effect represents the net effect of a number of different mechanisms that are individually complex, mutually interdependent and likely to vary in importance from one type of energy efficiency improvement to another. Estimating the magnitude of the economy-wide rebound effect in any particular instance is therefore very difficult. Nevertheless, the general implication is that the energy 'saved' from energy efficiency improvements will be less than is conventionally assumed.

The view that energy efficiency improvements will increase rather than reduce energy consumption was first put forward by the British economist, William Stanley Jevons, as long ago as 1865. It has subsequently become known as the 'Khazzoom-Brookes (K-B) postulate', after two contemporary economists (Len Brookes and Daniel Khazzoom) who have been closely associated with this idea.² In its original formulation, the K-B postulate³ states that:

'with fixed real energy prices, energy efficiency gains will increase energy consumption above what it would be without these gains' (Saunders, 1992).

If it were correct, the K-B postulate would have deeply troubling policy implications. It would imply that many of the policies used to promote energy efficiency may neither reduce energy consumption nor carbon emissions. The conventional assumptions of energy analysts, policymakers, business and lay people alike would be turned on their head. Alternatively, even if the postulate were incorrect, the various mechanisms described above could still make energy efficiency policies less effective in reducing energy consumption than is commonly assumed. In either case, the rebound effect could have important implications for global efforts to address climate change. But despite its potential importance, the topic is widely neglected and shrouded in controversy and confusion.

1 This may be expressed as $\frac{DIR}{IND}$, where ENG represents the expected energy savings from a particular energy efficiency improvement without taking rebound effects into account; DIR represents the increase in energy consumption resulting from the direct rebound effect; and IND represents the increase in energy consumption resulting from the indirect rebound effects.

2 The 'Jevons-Brookes postulate' would be a more accurate term, since Khazzoom's work focuses entirely on the direct rebound effect. Brookes, in contrast, is a strong advocate of the postulate at a macroeconomic level. An alternative term is 'Jevons Paradox' (Alcott, 2005).

3 The term postulate indicates a starting assumption from which other statements are logically derived. It does not have to be self-evident or supported by empirical evidence. But since most commentators do not accept the K-B postulate, this assessment treats it as a hypothesis and seeks out testable implications.



Box 1.2 Classifying rebound effects

The economy-wide rebound effect represents the sum of the direct and indirect effects. For energy efficiency improvements by consumers, it is helpful to decompose the direct rebound effect into:

- a) 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
- b) 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:

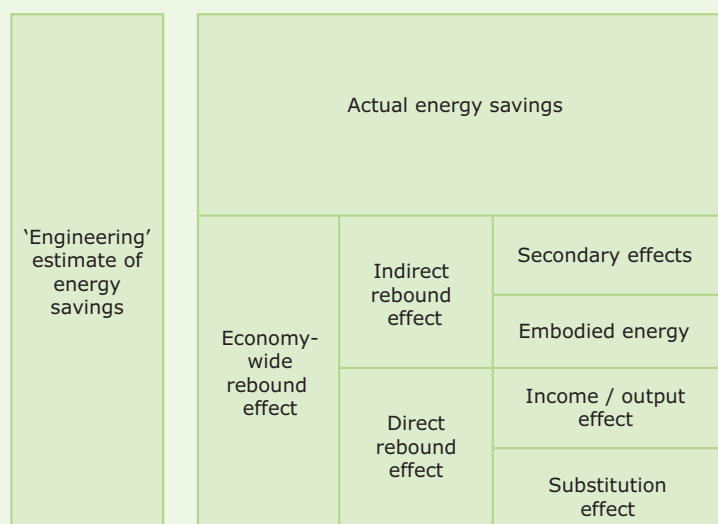
- a) a *substitution effect*, whereby the cheaper energy service substitutes for the use of capital, labour and materials in producing a constant level of output; and
- b) an *output effect*, whereby the cost savings from the energy efficiency improvement allows a higher level of output to be produced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

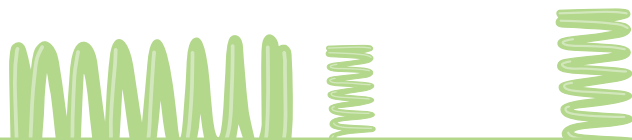
It is also helpful to decompose the indirect rebound effect into:

- a) 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
- b) the *secondary effects* that result as a **consequence** of the energy efficiency improvement, which include the mechanisms listed in Box 1.1.

A diagrammatic representation of this classification scheme is provided below (see also the *Supplementary Note*). 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. For example,

if an energy service is an 'inferior good', the income effect for consumers may lead to reduced consumption of that service, rather than increased consumption. It is theoretically possible for the economy-wide rebound effect to be negative ('super conservation'), although this appears unlikely in practice.





Rebound effects tend to be almost universally ignored in official analyses of the potential energy savings from energy efficiency improvements. A rare exception is UK policy to improve the thermal insulation of households, where it is expected that some of the benefits will be taken as higher internal temperatures rather than reduced energy consumption (DEFRA, 2007). But the direct rebound effects for other energy efficiency measures are generally ignored, as are the potential indirect effects for all measures. Much the same applies to energy modelling studies and to independent estimates of energy efficiency potentials by energy analysts. For example, the Stern Review of the economics of climate change overlooks rebound effects altogether (Stern, 2007), while the Fourth Assessment Report from the Intergovernmental Panel on Climate Change simply notes that the literature is divided on the magnitude of this effect (IPCC, 2007). Criticising this stance, the House of Lords Select Committee on Science and Technology commented that:

"...the Khazzoom Brookes postulate, while not proven, offers at least a plausible explanation of why in recent years improvements in 'energy intensity' at the macroeconomic level have stubbornly refused to be translated into reductions in overall energy demand. The Government have so far failed to engage with this fundamental issue, appearing to

rely instead on an analogy between micro- and macroeconomic effects." (HoL, 2006)⁴

While energy economists recognise that direct and indirect rebound effects may reduce the energy savings from energy efficiency improvements, there is dispute over how important these effects are - both individually and in combination. Some argue that rebound effects are of minor importance for most energy services, largely because the demand for those services appears to be inelastic⁵ in most cases and because energy typically forms a small share of the total costs of those services (Lovins, *et al.*, 1988; Lovins, 1998; Schipper and Grubb, 2000).⁶ Others argue that they are sufficiently important to completely offset the energy savings from improved energy efficiency (Brookes, 2000; Herring, 2006). At first sight, it appears odd for competent and experienced analysts to hold such widely diverging views on what appears to be an empirical question. This suggests one of three things: first, different authors may be using different definitions of the rebound effect, together with different definitions of associated issues such as the relevant system boundaries; second, the empirical evidence for rebound effects may be sufficiently sparse, ambiguous and inconclusive to be open to widely varying interpretations; or third, fundamental assumptions regarding how the economy operates may be in dispute.

4 This is strictly incorrect. First, the K-B postulate could explain a relatively slow rate of improvement in energy intensity; and second, to reduce overall energy demand the rate of improvement would need to be greater than the rate of GDP growth.

5 The own-price elasticity of demand for a good or service is the ratio of the relative (or percentage) change in quantity demanded to the relative change in price, holding other factors constant. In most cases, the own-price elasticity is negative. Demand is said to be inelastic when the own-price elasticity is less than one in absolute value, and elastic when it is greater than one.

6 The price of a service depends upon the total cost of providing that service, which includes capital, labour, materials and energy costs. If energy forms a small proportion of total costs, the elasticity of demand with respect to energy prices should be less than the own-price elasticity of demand with respect to total costs.

In practice, all of these factors appear to be relevant. The empirical evidence for direct rebound effects is very patchy, mainly focused on a limited number of consumer energy services such as personal automotive transport and almost wholly confined to OECD economies. Quantitative estimates of indirect and economy-wide rebound effects are rare, leaving authors such as Brookes (2000) to rely on an eclectic mix of theoretical argument, anecdotal examples and 'suggestive' evidence from econometric analysis and economic history. Much of this evidence rests upon theoretical assumptions and methodological approaches that are both highly technical and openly contested. There is also confusion, misunderstanding and disagreement over basic definitional issues such as the meaning of 'improvements in energy efficiency'. The result is that commentators talk past one another, with disagreements originating in part because different people are talking about different things. For example, some commentators appear to equate 'the' rebound effect solely with the direct effect, and thereby ignore the indirect effects that are the primary concern of economists such as Jevons. In particular, there appears to be a divergence between the world views of 'economists' and 'engineers':

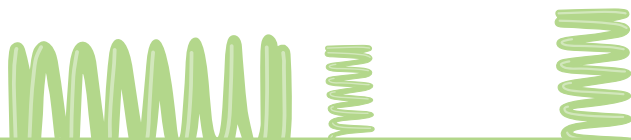
"For the economist the world is an open field in which different factors of production and different consumption goods have to be constantly re-combined in the most profitable fashion in response to their prices and marginal productivities. An efficiency increase in one factor immediately leads to a complete re-

arrangement due to implicit price changes and hence to a large rebound effect.....For the engineer, instead, the world consists of a set of given technologies or activities, which determine demand in which relative shares are fixed. Any increase in the productivity of one factor affects only that factor and hence there is no rebound effect." (Birol and Keppler, 2000)

Rebound effects could therefore be of considerable importance, but they are widely ignored by policy makers and their magnitude is greatly disputed, even among economists who understand the mechanisms involved. An assessment of the state of knowledge in this area should therefore make a valuable contribution to contemporary policy debates. At the same time, the diversity and ambiguity of the evidence base makes such an assessment challenging to conduct.

1.2 How the assessment was conducted

This assessment is one in a series being carried out by the Technology and Policy Assessment (TPA) function of the UK Energy Research Centre (UKERC). The selection of the rebound effect as a topic followed wide ranging consultation with stakeholders, together with advice from the TPA Advisory Group. The Group noted the persistence of controversy about the rebound effect, the existence of widely diverging views on the topic and the mismatch between the potential importance of the topic and the apparently limited research devoted to it. It also emphasised the importance of



addressing rebound effects ‘in the round’, including the indirect and economy-wide effects. This led the UKERC to undertake this study.

The objective of this assessment is not to undertake new research on rebound effects. Instead, it is to provide a thorough review of the current state of knowledge on this issue and to explain the findings in an accessible manner. The general approach was informed by the *systematic review* techniques prominent in medicine and other fields (see Box 1.3). Following this model, the assessment began with a Scoping Note that clarified the definition and nature of the rebound effect, identified the size and nature of the evidence base and set out the options for synthesising this evidence (Sorrell and

Dimitropoulos, 2005b). The diversity of the evidence base and the extent to which it is embedded in complex and contested theoretical issues was found to make the conventional systematic review techniques difficult to apply – a feature that is common to many policy-relevant questions in the energy field (Sorrell, 2007).

An Advisory Group for the project was established and the Scoping Note circulated to key stakeholders. This led to a series of recommendations on the appropriate scope and focus of the assessment, including the relative weight to be given to different sources of evidence. The agreed approach was then set out in an Assessment Protocol (Sorrell and Dimitropoulos, 2005a) which clarified that the assessment should update and

Box 1.3 Overview of the TPA approach

The TPA approach to assessment seeks to learn from a range of techniques referred to as Evidence Based Policy and Practice (EBPP), including meta-analyses of quantitative data and systematic reviews of quantitative and qualitative evidence. These aspire to provide more robust evidence for policymakers and practitioners, avoid duplication of research, encourage higher research standards and identify research gaps. However, energy policy presents a number of challenges for the application of systematic review techniques and the approach has been criticised for excessive methodological rigidity in some policy areas (Sorrell, 2007). The UKERC has therefore set up a process that is inspired by these approaches, but is not bound to any narrowly defined method or technique.

The process carried out for each assessment includes the following components:

- Publication of Scoping Note and Assessment Protocol.
- Establishment of a project team with a diversity of expertise.
- Convening an Expert Group with a diversity of opinion and perspective.
- Stakeholder consultation.
- Systematic searches of the the evidence base.
- Categorisation and assessment of evidence.
- Synthesis, review and drafting.
- Expert feedback on initial drafts.
- Peer review of final draft.

extend a previous literature review by Greening *et al.* (2000), place greater emphasis on indirect and economy-wide effects and focus in particular on clarifying the underlying conceptual frameworks and identifying the reasons for the widely diverging views. Since disputes over the rebound effect involve some highly technical concepts from economic theory and econometric practice, much emphasis has been placed on clarifying these concepts and making them accessible to a non-technical audience.

The assessment was organised around five broad categories of evidence, as follows:

- *Evaluation studies*: micro-level evaluations of the impact of specific energy efficiency improvements on the demand for energy or energy services;
- *Econometric studies*: use of secondary data sources to estimate the elasticity of the demand for energy or energy services at different levels of aggregation;
- *Elasticity of substitution studies*: estimates of the elasticity of substitution between energy and capital at different levels of aggregation;
- *Computable general equilibrium modelling studies*: estimates of economy-wide rebound effects from computable general equilibrium (CGE) models of the macroeconomy; and
- *Energy, productivity and economic growth studies*: a range of evidence considered in some way relevant to the K-B postulate, including studies from economic history, neoclassical

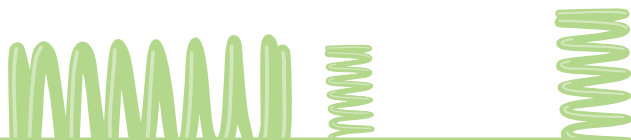
production theory, neoclassical growth theory, ecological economics, decomposition analysis, and input-output analysis.

The first two categories of evidence relate to direct rebound effects while the remainder relate to economy-wide rebound effects. The last category is especially diverse and has received the greatest amount of attention. While the project began with systematic literature searches using keyword such as 'rebound effect', the final assessment incorporates a much broader range of evidence, reviewing more than 500 studies from around the world. The full results of the assessment are reported in five in-depth *Technical Reports*, namely:

- *Technical Report 1*: Evidence from evaluation studies
- *Technical Report 2*: Evidence from econometric studies
- *Technical Report 3*: Evidence from elasticity of substitution studies
- *Technical Report 4*: Evidence from CGE modeling studies
- *Technical Report 5*: Evidence from energy, productivity and economic growth studies

In addition, a shorter *Supplementary Note* provides a graphical analysis of rebound effects. All these reports are available to download from the UKERC website.

The present report summarises the main conclusions of the assessment and identifies policy implications and priorities for further research.



1.3 Report structure

The report is structured as follows:

Section 2 describes the different definitions of energy efficiency, the choices available for the independent and dependent variables for the rebound effect and the implications of those choices for the estimated magnitude of the effect. It is argued that disputes over the magnitude of rebound effects result in part from confusion over these basic definitions.

Section 3 describes the nature and operation of direct rebound effects and summarises the evidence regarding the magnitude of these effects for a number of consumer energy services. It concludes that direct rebound effects appear to be low to moderate (i.e. <30%) for most consumer energy services in developed countries. Direct rebound effects may be larger in developing countries and for energy efficiency improvements by producers, but the empirical evidence for both is weak.

Section 4 describes the nature and operation of indirect and economy-wide rebound effects and summarises the results of a number of studies that provide quantitative estimates of these effects. This evidence base is both small and subject to a number of important methodological weaknesses, making it

difficult to draw any general conclusions. However, the available studies suggest that economy-wide rebound effects may frequently exceed 50%.

Section 5 summarises the evidence for the K-B postulate, focusing in particular on the work of W.S. Jevons, Len Brookes and Harry Saunders. Instead of providing quantitative estimates of rebound effects, the evidence discussed in this section provides indirect support for the K-B postulate and is taken from such diverse fields as neoclassical growth theory, economic history and econometric analysis of productivity trends. A core argument of this section is that the case for the K-B postulate hinges on the claim that energy plays a more important role in economic growth than is conventionally assumed. Much of the discussion therefore focuses on this broader issue and compares conventional views with the alternative perspective of ecological economics. It is argued that satisfactory resolution of the debate over the K-B postulate may hinge in part on a satisfactory resolution of this much broader question.

Finally, Section 6 summarises the key conclusions from the assessment, identifies the main research needs and highlights some important policy implications.





2. What is energy efficiency?

This section introduces the different definitions of energy efficiency and the different ways of measuring energy inputs and useful outputs. It argues that these definitional issues have important but generally unacknowledged implications for the estimated magnitude of rebound effects.

2.1 Energy efficiency and energy savings

Energy efficiency improvements are generally assumed to reduce energy consumption below where it would have been without those improvements. The rebound effect may reduce the size of these energy savings (Box 1.2). However, estimating the size of any 'energy savings' is far from straightforward, since:

- real-world economies do not permit controlled experiments, so the relationship between a change in energy efficiency and a subsequent change in energy consumption is likely to be mediated by a host of confounding variables;
- we can't observe what energy consumption 'would have been' without the energy efficiency improvement (the so-called 'counterfactual' scenario), so the estimated 'savings' from energy efficiency improvement will always be uncertain; and
- energy efficiency is not controlled externally by an experimenter and may be influenced by a variety of technical, economic and policy variables. In particular, the direction of causality may run in reverse - with

changes in energy consumption (whatever their cause) leading to changes in energy efficiency.

Energy efficiency may be defined as the ratio of 'useful' outputs to energy inputs for a system. The system in question may be an individual energy conversion device (e.g. a boiler), a building, an industrial process, a firm, a sector or an entire economy. In all cases, the measure of energy efficiency will depend upon how 'useful' is defined and how inputs and outputs are measured. When outputs are measured in thermodynamic or physical terms, the term energy efficiency tends to be used, but when outputs are measured in economic terms it is more common to use the term 'energy productivity'. The inverse of both measures is termed 'energy intensity'.

Improvements in energy efficiency may reduce the energy used by that system. For example, the installation of a condensing boiler may reduce the amount of gas used to heat a house. But a full accounting of rebound effects requires attention to be paid to the consequences for energy consumption within broader systems, such as the economy as a whole. For example, the money saved on heating costs may be spent on other goods and services which also require energy to provide.

The definition of inputs and outputs, the appropriate system boundaries for measures of energy efficiency and energy consumption and the timeframe under consideration can vary widely from one study to another. The conclusions drawn regarding the magnitude and importance of the rebound effect are likely to depend upon the particular choices that are made.



2.2 Multiple definitions

The most basic definition of energy efficiency derives from the first-law of thermodynamics and measures the ratio of 'useful' energy outputs to the heat content, or calorific value of fuel inputs. A conventional lightbulb, for example, has a first-law efficiency of only 6%, since 6% of the heat content of energy inputs are converted to light energy and the remainder is lost as 'waste' heat (Berndt, 1978; Patterson, 1996). But the first-law efficiency of a process depends upon how 'useful' is defined. When waste heat and other losses are taken into account, the first-law efficiency becomes 100%, since energy is not 'used up' but is merely transformed from 'available' to less available forms.

Although widely used, first-law efficiency measures are misleading because they do not take into account the availability of energy inputs and outputs, or their ability to perform *useful work*⁷ (Berndt, 1978). For example, energy in the form of high-pressure steam can perform more useful work than the same amount of energy in the form of low temperature heat. The thermodynamic concept of *exergy* provides a general measure of the ability to perform useful work and may be applied to both the inputs and outputs of conversion processes (Wall, 2004). The exergy content of an energy carrier may therefore be different from its heat content, although both are measured in kWh (kilowatt hours). For example, a heat unit of electricity will be ranked higher on

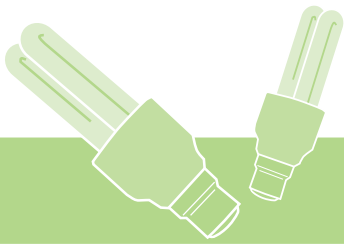
exergy basis than a heat unit of oil or natural gas. Also, unlike energy, exergy is 'consumed' in conversion processes.

The notion of exergy leads to a second definition of energy efficiency, based upon the second law of thermodynamics. This 'second-law' measure is frequently smaller than the first-law efficiency, suggesting a greater potential for improvement. For example, the first-law efficiency of electric resistance space heating may exceed 99%, but this falls to around 5% when a second-law definition is used (Rosen, 2004). The difference arises because resistance heating converts high exergy electricity to low exergy space heat. Second-law measures are preferable since they focus attention what needs to be conserved - namely exergy rather than energy per se (Berndt, 1978).

For most purposes, it is simpler to measure useful energy outputs in terms of *physical* indicators for the relevant energy service, rather than heat content or exergy. For example, a suitable output measure for personal transportation by private car could be vehicle kilometres. A physical measure of energy efficiency would then be vehicle kilometres per litre of motor fuel.

Physical measures may be applied at the level of individual energy conversion devices, but are more commonly applied at higher levels of aggregation, such as a household, an industrial process, an individual firm or an individual sector. In each case, changes in physical measures

⁷ 'Work' may be broadly defined as an increase in the kinetic, potential, physical or chemical energy of a subsystem that is located within a larger system in which energy - according to the first-law - is always conserved (Ayres, *et al.*, 2003).



may result from factors other than improvements in the thermodynamic efficiency of conversion devices. For example, changes in vehicle load factors will change a physical measure of energy efficiency that is based upon passenger kilometres per litre of motor-fuel. Appropriate physical indicators are likely to vary from one sector to another and one type of energy service to another, making an aggregate economy-wide physical measure of energy efficiency inappropriate.

By replacing the numerator with an indicator of the *economic* value of output, the energy efficiency of different sectors can be compared (Patterson, 1996). For example, the energy efficiency of both the brewing and dairy sectors can be measured in terms of value added per Gigawatt hours (GWh) of energy input. The move from physical to economic indicators increases the number of factors that could influence the indicator as does the use of such indicators at higher levels of aggregation. The indicator that is furthest from a thermodynamic measure of energy efficiency is therefore the ratio of GDP to total primary energy consumption within a national economy.

Hence, when using the terms energy efficiency and energy productivity, it is essential to clarify how the inputs and outputs are being measured. In what follows, the term *useful work* will be used in a generic sense to refer to the useful outputs of energy conversion systems.

Whichever measure is used, maximising energy efficiency is an inappropriate goal since it does not take into account the costs associated with other inputs such as

capital and labour. Economists are therefore more concerned with improving *total factor productivity* (TFP), which is a measure of the efficiency with which all inputs are used by a firm, sector or national economy.

The energy efficiency improvements that are of most relevance to the rebound effect are those that are consistent with the best use of all economic resources. These are conventionally divided into two categories: those that are associated with improvements in total factor productivity ('technical change'), and those that are not ('substitution'). The former are conventionally assumed to occur independently of changes in relative prices, while the latter are assumed to occur in response to such changes (Box 2.1). This distinction is potentially misleading, however, since it assumes that the producer is making fully efficient use of all relevant inputs. Many energy efficiency improvements may be better described as 'overcoming inefficiency', since they represent the use of existing technologies to move closer to an 'optimal' combination of inputs (Box 2.1). This type of improvement also improves total factor productivity and may frequently be stimulated through non-price energy efficiency policies.

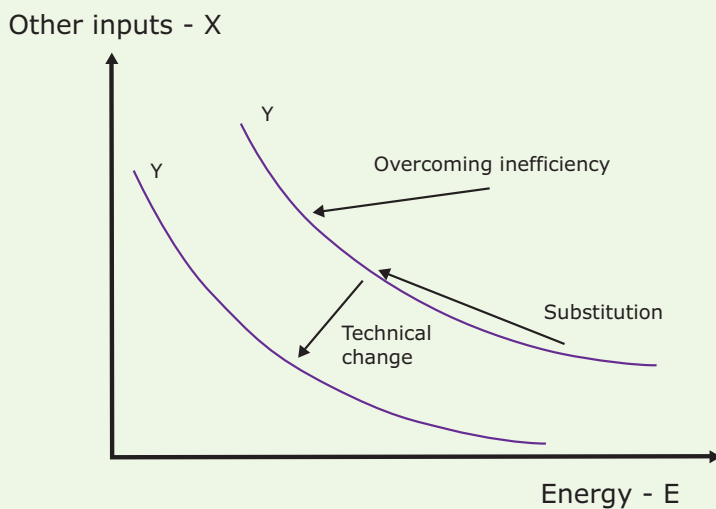
Rebound effects may be defined in relation to each type of energy efficiency improvement, although most studies classify such improvements as deriving from either substitution or technical change. The consequences of technical change are of particular interest, since this contributes to the growth in economic output. Also, many (if not most) energy efficiency improvements are likely to be



Box 2.1 Types of energy efficiency improvement

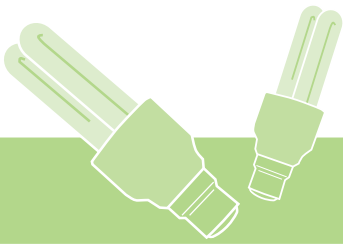
Increases in energy prices may lead to improvements in energy efficiency (or energy productivity) of a system through the *substitution* of capital or labour inputs for energy. For example, thermal insulation may reduce the consumption of gas for space heating. But if the prices of other inputs are unchanged the total cost of producing a given level of output will have increased. In contrast, improvements in both energy productivity and total factor productivity may result from *technical change*. This is conventionally assumed to occur independently of any change in relative prices and is considered desirable since it occurs without any reduction in economic output.

In neoclassical economics, a production function represents the maximum possible flow of output (Y) obtainable from the flow of energy (E) and other inputs (X), given the current state of technology (see diagram). An 'isoquant' of a production function represents the different possible combination of inputs that may be used to produce a given level of output. The 'optimal' combination depends upon the relative prices of those inputs. *Substitution* may be represented a movement *along* an isoquant in response to a change in relative prices. This may require investment in technologies that



can combine inputs in different ways (e.g. energy-efficient motors), but these are assumed to be chosen from a set of existing technologies. In contrast, *technical change* refers to the development of new technologies and methods of organisation that *shift* the isoquant to the left, allowing the same level of output to be produced from a lower level of inputs.

In practice, the conventional distinction between substitution and technical change can be misleading. First, the notion of substitution implies a 'frictionless' move from one existing technique to another, but in practice this requires investment and will take time. Second, technical change is not autonomous but is influenced by changes in relative prices and much contemporary research is concerned with improving understanding of this process (Grubb, *et al.*, 2002). Third, the production function represents the most efficient combination of factor inputs, but in practice firms may use relatively inefficient combinations. Much investment may be better represented as a move from less efficient to more efficient combinations, while still remaining within the production function 'frontier' - indicated by the 'overcoming inefficiency' arrow in the diagram.



the by-product of attempts to improve total factor productivity, rather than the result of targeted efforts to improve energy efficiency.

Technical change is said to be 'neutral' if it reduces the use of all inputs by an equal amount and 'biased', if it reduces the use of some inputs more than others. 'Energy-saving' technical change reduces the share of energy in the value of output by proportionately more than the share of other inputs, while 'energy-using' technical change does the reverse. This bias in technical change is closely related to (but not the same as) the rate of growth of energy efficiency over time, holding relative prices constant, which is an important parameter in many energy-economic models (Löschel, 2002; Sanstad, *et al.*, 2006).

2.3 Unacknowledged implications

The importance of these definitional issues for estimates of the rebound effect is not often recognised. Many commentators assume that the relevant independent variable for the rebound effect is improvements in the *thermodynamic efficiency* of individual conversion devices or industrial processes. But such improvements will only translate into comparable improvements in *different* measures of energy efficiency, or measures of energy efficiency applicable to wider system boundaries, if several of the mechanisms responsible for the rebound effect fail to come into play. For example, improvements in the number of litres

used per vehicle kilometre will only translate into improvements in the number of litres used per passenger kilometre if there are no associated changes in average vehicle load factors.

Rebound effects may be expected to increase over time and with the widening of the system boundary for the dependent variable (energy consumption). For example, the energy savings for manufacturing as a whole may be expected to be less than the energy savings for an individual firm that invests in an energy efficient technology. For the K-B postulate the relevant system boundary is normally taken as the national economy. But energy efficiency improvements may also affect trade patterns and international energy prices, thereby changing energy consumption in other countries. For the purpose of assessing the contribution of energy efficiency to reducing carbon emissions, the relevant system boundary is the whole world. To capture the full range of rebound effects, the system boundary for the independent variable (energy efficiency) should be relatively narrow, while the system boundary for the dependent variable (energy consumption) should be as wide as possible. For example, the independent variable could be the energy efficiency of an electric motor, while the dependent variable could be economy-wide energy consumption. However, measuring or estimating the economy-wide effects of such micro-level changes effects is, at best, challenging. For this reason, the independent variable for many theoretical and empirical studies of rebound effects is a physical or economic measure of energy efficiency



that is applicable to relatively wide system boundaries – such as the energy efficiency of an industrial sector. But such studies may overlook the ‘lower-level’ rebound effects resulting from improvements in physical or thermodynamic measures of energy efficiency appropriate to narrower system boundaries. For example, improvements in the energy efficiency of electric motors in the engineering sector may lead to rebound effects within that sector, with the result that the energy intensity of that sector is reduced by less than it would be in the absence of such effects. But if the energy intensity of the sector is taken as the independent variable, these lower-level rebound effects will be overlooked. Also, improvements in more aggregate measures of energy efficiency are unlikely to be caused solely (or even mainly) by the diffusion of more thermodynamically efficient conversion devices.

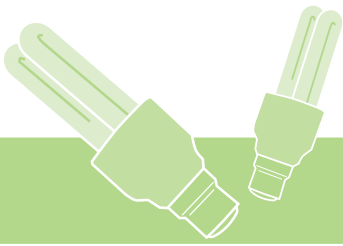
Aggregate measures of energy efficiency will depend upon how different types of energy input are combined. The most common approach is to aggregate different energy types according to their heat content, but this neglects the ‘quality’ of each energy type, or the ability to perform useful work. The latter, in turn, is only one of several factors that determine the economic productivity of different energy types, with others including cleanliness, amenability to storage, safety, flexibility of use and so on, together with the use to which the energy is put (Cleveland, *et al.*, 2000). In the absence of significant market distortions, the relative price per kilowatt

hour of different energy carriers can provide a broad indication of their relative marginal productivities (Kaufmann, 1994).⁸

Using data on relative prices, economists have devised methods for aggregating energy types of different marginal productivities (Berndt, 1978). In general, when the ‘quality’ of energy inputs are accounted for, aggregate measures of energy efficiency are found to be improving more slowly than is commonly supposed (Hong, 1983; Zarnikau, 1999; Cleveland, *et al.*, 2000). For example, on a thermal input basis, per-capita energy consumption in the US residential sector decreased by 20% over the period 1970 to 1991, but when adjustments are made for changes in energy quality (notably the increasing use of electricity), per capita energy consumption is found to have increased by 7% (Zarnikau, *et al.*, 1996). This difference demonstrates that technical progress in energy use is not confined to improvements in thermodynamic efficiency, but also includes the substitution of low quality fuels by high quality fuels (notably electricity), thereby increasing the amount of utility or economic output obtained from the same heat content of input (Kaufmann, 1992).

Failure to allow for this can lead to misleading conclusions. For example, it is commonly assumed that a combination of structural change and ‘energy efficiency’ improvements have allowed OECD countries to decouple GDP growth from the growth in primary energy

⁸ The marginal product of an energy input into a production process is the marginal increase in the value of output produced by the use of one additional heat unit of energy input.



consumption (Geller, *et al.*, 2006).⁹ However, if energy inputs are weighted by their relative marginal productivities, the growth in energy consumption is shown to be closely coupled to the growth in GDP (Hong, 1983; Stern, 1993; Cleveland, *et al.*, 2000; Stern and Cleveland, 2004). Hence, not only may such 'decoupling' be partly illusory, but the contribution of improved thermodynamic efficiency to any decoupling may easily be overstated.

Both fuel switching and improvements in the thermodynamic efficiency of conversion devices may be expected to change aggregate measures of energy efficiency, but the rebound effects associated with each may be different. Also, improvements in any measure of energy efficiency rarely occur in isolation but are typically associated with broader improvements in the productivity of other inputs, with new technologies frequently providing both. Pye and McKane (1998), for example, show how the installation of energy efficient motors can reduce wear and tear, extend the lifetime of system components and achieve savings in capital and labour costs that exceed the reduction in energy costs. Hence, if the *full* impact on energy consumption of a new energy-efficient technology is taken as the appropriate dependent variable, then the estimated (direct, indirect or economy-wide) rebound effect may be larger. Conversely, if only a portion of this impact is attributed specifically to the energy efficiency improvement, then the estimated rebound effect may be smaller. However, it is both difficult and misleading

to isolate the impact on energy demand of an improvement in energy efficiency alone. What matters for policy is how a new, energy-efficient *technology* affects overall energy demand. This frequently overlooked point is a major theme of this assessment.

2.4 Summary

- Energy efficiency may be measured in a variety of ways for a variety of system boundaries and any one of these may form an appropriate independent variable for an estimate of the rebound effect. While the appropriate choice depends upon the objectives of the study, difficulties may arise if commentators interpret the term 'energy efficiency' in different ways.
- The dependent variable for the rebound effect is a change in energy consumption, which may also be measured for a variety of system boundaries. However, wider system boundaries allow a greater range of rebound effects to be captured.
- Many theoretical and empirical studies of rebound effects employ physical or economic measures of energy efficiency applicable to relatively wide system boundaries. But these may overlook the rebound effects resulting from improvements in physical or thermodynamic measures of energy efficiency appropriate to narrower system boundaries.

⁹ If energy is measured in terms of heat content, major OECD countries used one third less primary energy to generate a unit of GDP than in the early 1970s (Geller, *et al.*, 2006).



- Many theoretical and empirical studies aggregate different types of energy carrier on the basis of their thermal content, thereby neglecting differences in energy quality. This may lead such studies to overlook the contribution of changes in fuel mix to changes in aggregate measures of energy efficiency. If energy inputs are weighted by their relative marginal productivities, the historical growth in energy consumption appears to be closely coupled to the growth in GDP.
- Economists are primarily interested in energy efficiency improvements that are consistent with the best use of all economic resources. These are commonly categorised as either price-induced substitution or technical change, but this neglects the importance of organisational and market failures in contributing to inefficiencies as well as the role of relative prices in stimulating technical change.
- Energy efficiency improvements by producers may often be associated with improvements in the productivity of capital, labour and materials inputs. Similarly, energy efficiency improvements by consumers may often save costs on more than energy alone. This needs to be allowed for when estimating rebound effects, as does any associated changes in fuel mix. Failure to do so may lead to rebound effects being underestimated and to the potential for decoupling between energy consumption and economic output to be overestimated.



3. The evidence for direct rebound effects

This section summarises the empirical evidence for direct rebound effects, focusing in particular on energy services in the household sector, since this is where the bulk of the research has been undertaken. A full examination of this evidence is contained in *Technical Report 1* and *Technical Report 2*.

Section 3.1 describes the operation of the direct rebound effect, highlighting some key issues concerning the measurement of this effect and the conditions under which it may be expected to be larger or smaller. The *Supplementary Note* contains a simple graphical analysis of rebound effects that complements the discussion in this section.

Section 3.2 describes one approach to estimating direct rebound effects that use quasi-experimental methodologies adopted from the field of policy evaluation. It then summarises the results of a limited number of studies that use this approach to estimate direct rebound effects from energy efficiency improvements in space heating.

Section 3.3 describes an alternative and more commonly used approach to estimating direct rebound effects that uses econometric analysis of secondary data sources to estimate the elasticity of demand for either useful work or energy consumption. Sections 3.4 and 3.5 summarise the results of a number of studies that use this approach to estimate direct rebound effects for personal automotive transport, household heating and a limited number of other consumer energy services. Section 3.6 discusses a number of potential sources of bias with this approach that may lead the direct rebound effect to be overestimated. Section 3.7 concludes.

3.1 Understanding the direct rebound effect

Direct rebound effects relate to individual energy services, such as heating, lighting and refrigeration and are confined to the energy required to provide that service. Improved energy efficiency will decrease the marginal cost of supplying that service and should therefore lead to an increase in consumption of the service. For example, consumers may choose to drive further following the purchase of energy efficient car because the price per kilometre has fallen. The resulting increase in energy service consumption will tend to offset the expected reduction in energy consumption provided by the energy efficiency improvement.

As shown in Box 1.2, the direct rebound effect for consumers may be decomposed 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'; and an *income effect*, whereby the increase in real income achieved by the energy efficiency improvement allows increased consumption of the energy service. In a similar manner, the direct rebound effect for producers may be decomposed into a substitution effect and an output effect (see *Supplementary Note*). Also, for most energy services, the direct rebound effect may be expected to increase over time as markets, technologies and behaviours adjust. For example, energy efficiency improvements may lower production costs for a firm, but it may take time for the firm to increase output and market share.



Energy services are provided through a combination of capital equipment, labour, materials and energy. An essential feature of an energy service is the *useful work* obtained which, as shown in Section 2, may be measured by a variety of ways. For example, the useful work from passenger cars may be measured in vehicle kilometres, passenger kilometres or (rather unconventionally) in tonne kilometres. Energy services may also have broader attributes 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. Consumers and producers may therefore make trade-offs between useful work and other attributes of an energy service; between energy, capital and other market goods in the production of an energy service; and between different types of energy service.

By reducing the marginal cost of useful work, energy efficiency improvements may, over time, lead to an increase in the number of energy conversion devices, their average size, their average utilisation and/or their average load factor. For example, people may buy more cars, buy larger cars, drive them further and/or share them less. Similarly, people may buy more washing machines, buy larger machines, use them more frequently and/or reduce the size of the average load. The relative importance of these variables may be expected to vary widely between different energy services and over time. For example, technological improvements in the energy efficiency of new refrigerators are unlikely to increase

the average utilisation of the refrigerator stock (measured in hours/year) but could lead to a long-term increase in both the number of refrigerators and their average size (since the cost per cubic metre of refrigeration has fallen). Over the very long-term, the lower cost of energy services may contribute to fundamental changes in technologies, infrastructures and lifestyles - such as a shift towards car-based commuting and increasing distances between residential, workplace and retail locations. But as the time horizon extends, the effect of such changes on the demand for the energy service (as well as the demand for other goods and services) becomes increasingly difficult to separate from the effect of income growth and other factors.

The estimated size of the direct rebound effect depends upon how useful work and hence energy efficiency is defined. For example, the majority of estimates of the direct rebound effect for personal automotive transport measure useful work in terms of vehicle kilometres travelled, which is sometimes decomposed into the product of the number of vehicles and the mean distance travelled per vehicle per year (Greene, *et al.*, 1999b; Small and Van Dender, 2005). Energy efficiency is then defined as vehicle kilometres per litre of fuel and rebound effects are measured as increases in distance driven. But this overlooks any changes in mean vehicle size and weight as a result of energy efficiency improvements (e.g. more SUVs), as well as any decrease in average vehicle load factor (e.g. less car sharing). If energy efficiency was measured instead as tonne kilometres per litre of fuel,



rebound effects would show up as an increase in tonne kilometres driven, which may be decomposed into the product of the number of vehicles, the mean vehicle weight and the mean distance travelled per vehicle per year. To the extent that vehicle weight provides a proxy for factors such as comfort, safety and carrying capacity, this approach effectively incorporates some features normally classified as attributes of the energy service into the measure of useful work. It also moves closer to a thermodynamic measure of energy efficiency, by focusing upon the movement of mass rather than the movement of people.

The magnitude of direct rebound effects may be expected to be proportional to the share of energy in the total cost of energy services¹⁰, as well as the extent to which those costs are 'visible' to the consumer.¹¹ But as the consumption of a particular energy service increases, saturation effects (technically, declining marginal utility) should reduce the size of any direct rebound effect. For example, direct rebound effects from improvements in the energy efficiency of household heating systems should decline rapidly once whole-house indoor temperatures approach the maximum level for thermal comfort. One important implication is that direct rebound effects will be higher among low income groups, since these are further from satiation in their consumption of many energy services (Boardman and Milne, 2000).

Increases in demand for an energy service may derive from existing consumers of the service, or from consumers who were previously unable or unwilling to purchase that service. For example, improvements in the energy efficiency of home air-conditioners may encourage consumers to purchase portable air-conditioners for the first time. The abundance of such 'marginal consumers' (Wirl, 1997) in developing countries points to the possibility of large rebounds in these contexts, offset to only a limited extent by saturation effects among existing consumers (Roy, 2000).

While energy efficiency improvements reduce the energy cost of energy services, the size of the direct rebound effect will depend upon how other costs are affected. For example, direct rebound effects may be smaller if energy efficient equipment is more expensive than less efficient alternatives, because such improvements should not encourage an increase in the number and capacity of conversion devices. However, once purchased, such devices may be expected to have a higher utilisation. In practice, many types of equipment appear to have both improved in energy efficiency over time and fallen in total cost relative to income.

Even if energy efficiency improvements are not associated with changes in capital or other costs, certain types of direct rebound effect may be constrained by the

10 For example, if energy accounts for 50% of the total cost of an energy service, doubling energy efficiency will reduce the total costs of the energy service by 25%. But if energy only accounts for 10% of total costs, doubling energy efficiency will reduce total cost by only 5%. In practice, improvements in energy efficiency may themselves be costly.

11 For example, Kempton and Montgomery (1982) have compared the information value of the average household energy bill to that of receiving a single monthly bill from the supermarket for 'food'. Recent developments in smart metering and electronic display technologies offer the opportunity to improve the information available to consumers, and this could potentially make the demand for consumer energy services more price elastic.



real or opportunity costs associated with increasing demand. Two examples are the opportunity cost of space (e.g. increasing refrigerator size may not be the best use of available space) and the opportunity cost of time (e.g. driving longer distances may not be the best use of available time). However, space constraints may become less important over time if technological improvements reduce the average size of conversion devices per unit of output or if rising incomes lead to an increase in average living space (e.g. compare refrigerator sizes in the US and the UK) (Wilson and Boehland, 2005). In contrast, the opportunity cost of time should increase with rising incomes. As with energy price elasticities, therefore, the direct rebound effect for a particular energy service may be expected to vary over time and to be influenced by income and other variables.

3.2 Estimating direct rebound effects from evaluation studies

One approach to estimating the direct rebound effect is to measure the change in demand for useful work following an energy efficiency improvement: for example, measuring the change in internal temperatures following the installation of a fuel-efficient boiler. The demand for useful work before the energy efficiency improvement could be taken as an estimate for what demand 'would have been' in the absence of the improvement. However, various other factors may also

have changed the demand for useful work which needs to be controlled for.

Since it can be very difficult to measure useful work for many energy services (Box 3.1), an alternative approach is to measure the change in energy consumption for that service following an energy efficiency improvement. But to estimate direct rebound effects, this needs to be compared with a counterfactual scenario for energy consumption that has at least two sources of error, namely: a) the energy consumption that would have occurred without the energy efficiency improvement; and b) the energy consumption that would have occurred following the energy efficiency improvement had there been no behavioural change. The first of these gives an estimate of the energy savings from the energy efficiency improvement, while the second isolates the rebound effect. Estimates for the latter can be derived from engineering models, but these frequently require data on the circumstances of individual installations and are prone to error.

Both these approaches are analogous to the policy evaluation strategies employed in areas such as health and labour economics, but these appear to be relatively rare in the energy field owing in part to measurement difficulties (Frondel and Schmidt, 2005). There are relatively few published studies and nearly all of these studies focus on consumer energy services. Nadel (1993) reports the results of a number of evaluation studies by US utilities, which suggest direct rebound



effects of 10% or less for lighting and approximately zero for water heating, with inconclusive results for refrigeration. We have not been able to access these studies, which appear to be small-scale, short-term and methodologically weak. Instead, we summarise the results of 15 studies of household heating.

These studies use a variety of approaches to study a range of energy efficiency improvements for different types of household and different income groups, mostly within the US or UK. The methodological quality of most of these studies is relatively poor, with the majority using simple before and after comparisons, without the use of a control group or explicitly controlling for confounding variables. This is the weakest evaluation strategy and prone to bias (Meyer, 1995; Frondel and Schmidt, 2005). Also, several studies are subject to selection bias, since households choose to participate rather than being randomly assigned (Hartman, 1988). While techniques are available to control for this, they are rarely used (Berry, 1983; Train, 1994). Other methodological weaknesses include: small sample sizes contributing to low statistical power;¹² high variance in results and a frequent failure to present the error associated with estimates; large variation in the relevant independent variable both within and between studies (e.g. participating households receiving different types of

energy efficiency measure, or combinations of measures); monitoring periods that are too short (e.g. one month) to capture either long-term behavioural changes or seasonal variations in behavioural response; and so on. These weaknesses reduce the degree of confidence in the results and create difficulties in comparing the results of different studies.

For household heating, it is helpful to distinguish between:

- *shortfall*, representing the difference between actual savings in energy consumption and those expected on the basis of engineering estimates;
- *temperature take-back*, representing the change in internal temperature following the energy efficiency improvement; and
- *behavioural change*, representing the proportion of change in internal temperature that derives from adjustments of heating controls and other variables by the user (e.g. opening windows).

Typically, only a portion of temperature take-back is due to behavioural change, with the remainder being due to physical and other factors (Sanders and Phillipson, 2006).¹³ Similarly, only a portion of shortfall may be due to temperature take-back, with the remainder being due to

¹² The power of a statistical test is the probability that the test will reject a false null hypothesis.

¹³ For example, daily average household temperatures will generally increase following improvements in thermal insulation, even if the heating controls remain unchanged. This is because insulation contributes to a more even distribution of warmth around the house, reduces the rate at which a house cools down when the heating is off and delays the time at which it needs to be switched back on (Milne and Boardman, 2000).



poor engineering estimates of potential savings, inadequate performance of equipment, deficiencies in installation and so on.¹⁴ Hence, behavioural change is one, but not the only (or necessarily the most important) explanation of temperature take-back and the latter is one, but not the only explanation of shortfall. Several studies misleadingly equate shortfall with behavioural change and fail to specify the relevant uncertainties.

Direct rebound effects are normally interpreted as a behavioural response to lower energy service prices and hence may be best approximated by the behavioural change identified above. But it may be misleading to interpret this change solely as a rational response to lower heating costs, partly because energy efficiency improvements frequently change other variables (e.g. airflow) that also encourage behavioural responses. Also, measures of temperature take-back may be difficult to translate into estimates of shortfall because of a non-linear and household-specific relationship between energy consumption and internal temperature.

Measurement of behavioural responses requires thermostat settings to be monitored directly, which is neither straightforward nor common. Instead, most studies monitor internal temperatures and/or energy consumption and focus upon temperature take-back and/or shortfall, which are frequently more relevant to public policy. Unfortunately, different studies using

different terms for the above concepts as well as the same term for different concepts. The UK government uses the term 'comfort factor' to refer to the shortfall from household insulation improvements, but it could be misleading to equate this with the direct rebound effect.

The results from evaluation studies of household heating are difficult to compare owing to different approaches, inconsistent methodologies and different definitions of both the dependent and independent variables. Some studies report temperature take-back, some report shortfall and some make an estimate of behavioural change.

Without exception, the studies demonstrate a clear shortfall in energy savings due to space heating efficiency measures. The absolute magnitude of this difference varies between studies, but is generally between 10% and 50% of expected savings. In some studies a larger shortfall was found – for example, an evaluation of a UK programme for low income households found that the introduction of a more efficient heating system had no impact on reducing fuel consumption (Hong, *et al.*, 2006). However, overall percent shortfall is highly contingent on the accuracy of the engineering models, and attempts to calibrate these models to specific household conditions generally result in a lower shortfall. The studies use a wide range of variables to explain shortfall, but only initial energy consumption and the age of the home consistently influence the

¹⁴ For example, Hong *et al.* (2006) report the results of thermal camera imaging of houses following insulation improvements, which showed that 20% of the cavity wall area was missing insulation as well as 13% of the loft area.



Box 3.1 Measurement issues for the direct rebound effect

Measurement difficulties make estimation of direct rebound effects problematic at best and impossible at worst. For many energy services, the relevant data is simply unavailable, while for others the data must either be estimated or is subject to considerable error.

Measurement of useful work is extremely problematic, which partly explains why the empirical literature is largely confined to passenger transport, household heating and household cooling where suitable proxies are available. Aggregate measures of useful work are only available for a subset of energy services (e.g. vehicle kilometres for passenger transport), while disaggregate measures may require expensive monitoring of individual firms or households. In the case of household heating, a number of studies have monitored thermostat settings or internal temperatures for individual households (Greening and Greene, 1998). But to assess the full benefits of the efficiency improvement, the temperature change in each room of the building would need to be measured, while controlling for outside temperature, changes in occupancy and other factors. In addition, internal temperature is only one of the determinants of thermal comfort, with others including activity levels, air velocity, relative humidity and the mean radiant temperature of the surrounding surfaces (Fanger, 1970; Frey and Labay, 1988). Failure to take these into account could lead to biased estimates of the direct rebound effect (Friedman, 1987; Greening and Greene, 1998).

Data on the energy consumption for individual consumer energy services is rarely available, except when those services are sub-metered as part of an evaluation exercise. Data on total household energy consumption may be relatively accurate, but techniques such as 'conditional demand analysis' are required to estimate the proportion going to lighting, water heating, cooking and so on (Parti and Parti, 1980). Problems may even arise in well-studied areas such as personal automotive transport, where there is uncertainty over the proportion of total petrol and diesel consumption attributable to passenger cars, as well as the distance travelled by different types of vehicle (Schipper, *et al.*, 1993).

If data on both energy consumption and useful work is available, system-wide energy efficiencies can be estimated. Alternatively, the demand for useful work could be estimated from data on energy consumption and system-wide energy efficiency. But the latter is difficult to obtain, subject to inaccuracy and (depending upon the system boundary) frequently dependent upon variables other than the thermodynamic efficiency of conversion devices.

Empirical studies are more informative if the demand for useful work can be decomposed into the product of the number, capacity and utilisation of the relevant energy conversion devices, but usually this data is unavailable or subject to error. For example, several studies of personal automotive transport combine data on the number of vehicles, the distance driven, total energy consumption and average fuel efficiency that have not been independently and accurately determined. (Schipper, *et al.*, 1993). Also, the available data on useful work may not reflect the full range of direct rebound effects.

Measurement difficulties also apply to exogenous variables that affect the demand for energy, useful work or energy efficiency, such as demographic and geographical factors. Omission of such variables could lead to bias if they are correlated with the dependent or independent variables, while inclusion of such variables could lead to error if they are measured or estimated inaccurately.



extent to which predicted savings are likely to be achieved.

Some positive temperature take-back was observed in most studies; however it was frequently small and not always statistically significant. Take-back appeared to average between $\sim 0.4^{\circ}\text{C}$ and 0.8°C . Of this, approximately half was estimated to be accounted for by the physical characteristics of the house and the remainder by behavioural change. In homes with higher temperature take-back, the physical contribution remains the same and the behavioural contribution increases. This take-back is not trivial: a 1°C increase in internal temperature may increase the energy consumption for space heating by 10% or more.

Only a subset of the studies that measure temperature take-back provide estimates of the effect on energy savings and those that do vary widely, partly as a consequence of the different metrics used to present the effect. The likelihood of observing temperature take-back appears to be negatively correlated with income, as well as internal household temperatures prior to the efficiency measure. However, these two explanatory variables are likely to be correlated. As pre-intervention room temperatures approach 21°C the magnitudes of temperature take-back decreases owing to saturation effects.

Estimates of temperature take-back appear comparable between US and UK studies, with most showing a relatively small temperature increase for the average home and higher temperature increases for homes with low initial temperatures. UK average indoor

temperatures appear to be lower than in the US, but have been increasing over recent years irrespective of the energy efficiency measures installed.

In summary, the evaluation studies suggest that standard engineering models may overestimate the energy savings from energy efficiency improvements in household heating systems by up to one half – and potentially by more than this for low income households. However, temperature take-back only accounts for a portion of this shortfall and behavioural change only accounts for a portion of the take-back. This suggests that the direct rebound effect for this energy service should typically be less than **30%**. Rebound effects may be expected to decrease over time as average internal temperatures increase.

3.3 Estimating direct rebound effects from econometric studies

The 'evaluation' approach to estimating the direct rebound effect requires data to be collected on the demand for energy or useful work both before and after an energy efficiency improvement. This 'program focused' approach is relatively uncommon. Instead, most studies rely upon secondary data sources, frequently collected for other purposes that include information on the demand for energy, useful work and/or energy efficiency. This data can take a number of forms (e.g. cross-sectional, time-series) and apply to different levels of aggregation (e.g. household, region, country). Such studies



typically use a variety of econometric techniques to estimate *elasticities*, meaning the percentage change in one variable following a percentage change in another, holding other variables constant. If time-series data is available, an estimate can be made of short run elasticities, where the stock of conversion devices is assumed to be fixed, as well as long-run elasticities where it is variable. Cross-sectional data is usually assumed to provide estimates of long-run elasticities.

Depending upon data availability, the direct rebound effect may be estimated from one of *two energy efficiency* elasticities:¹⁵

E1 the elasticity of the demand for energy with respect to energy efficiency

E2 the elasticity of the demand for useful work with respect to energy efficiency

(E2) is generally taken as a direct measure of the rebound effect. Under certain assumptions, it can be shown that: $(E1)=(E2)-1$ (see *Technical Report 2*). The actual saving in energy consumption will only equal the predicted saving from engineering calculations when the demand for useful work remains unchanged following an energy efficiency improvement (i.e. $(E2)=0$).^{15a}

But instead of using (E1) or (E2), the majority of studies estimate the rebound effect from one of three *price* elasticities:

E3 the elasticity of the demand for useful work with respect to the price of useful work

E4 the elasticity of the demand for useful work with respect to the price of energy

E5 the elasticity of the demand for energy with respect to the price of energy

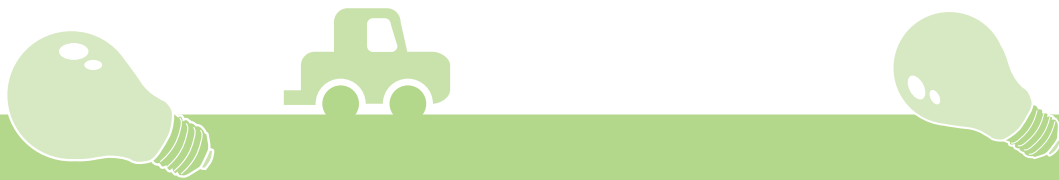
Under certain assumptions, the negative of (E3), (E4) or (E5) can be taken as an approximation to (E2). The use of price elasticities in this way implicitly equates the direct rebound effect to the behavioural responses identified in Section 3.2 and ignores the other reasons why the demand for useful work may change following an improvement in energy efficiency.

Estimates of (E1) (E2) and (E3) require data on energy efficiency for the relevant energy service, while estimates of (E3) (E4) and (E5) require data on energy prices. Generally, the latter tends to be both more available and more accurate than the former. Similarly, estimates of (E2) (E3) and (E4) require data on the demand for useful work, while estimates of (E1) and (E5) require data on the demand for energy. Again, the latter tends to be both more available and more accurate than the former.

In principle, estimates of either (E1) or (E2) should provide the best

15 The rationale for the use of these elasticities, and the relationship between them, is explained in detail in Technical Report 2. In the case of personal automotive transport, they could correspond to: (E1) the elasticity of the demand for motor-fuel (for passenger cars) with respect to kilometres per litre (E2) the elasticity of the demand for vehicle kilometres with respect to kilometres per litre; (E3) the elasticity of the demand for vehicle kilometres with respect to the cost per kilometre; (E4) the elasticity of the demand for vehicle kilometres with respect to the price of motor-fuel; and (E5) the elasticity of the demand for motor-fuel with respect to the price of motor-fuel.

15a Under these circumstances, $(E1)=-1$. A positive rebound effect implies that $(E2)>0$ and $0>(E1)>-1$, while backfire implies that $(E2)>1$ and $(E1)>0$.



approximation to the direct rebound effect. However, most data sets provide only limited variation in energy efficiency, with the result that estimates of (E1) and (E2) have a large variance. This is another reason why estimates of (E1) and (E2) are relatively rare.

In contrast, (E3) generally provides significantly greater variation in the independent variable. This is because the price of useful work depends upon the ratio of energy prices to energy efficiency and most data sets include considerable cross-sectional or longitudinal variation in energy prices. In principle, rational consumers should respond in the same way to a decrease in energy prices as they do to an improvement in energy efficiency (and vice versa), since these should have an identical effect on the price of useful work. However, there may be a number of reasons why this 'symmetry' assumption does not hold (see below). If so, estimates of the direct rebound effect that are based upon (E3) could be biased.

In many cases, data on energy efficiency is either unavailable or inaccurate. In these circumstances, (E4) and (E5) allow the direct rebound effect to be estimated solely from data on energy prices. But these are only valid if: first, consumers respond in the same way to a decrease in energy prices as they do to an improvement in energy efficiency (and vice versa); and second, energy efficiency is unaffected by changes in energy prices. Both these assumptions are likely to be

flawed, but the extent to which this leads to biased estimates of the direct rebound effect may vary widely from one energy service to another and between the short and long term.

Under certain assumptions, the own-price elasticity of energy demand (E5) can be shown to provide an *upper bound* for the direct rebound effect (see *Technical Report 2*). As a result, the voluminous literature on energy price elasticities may be used to place some bounds on the likely magnitude of the direct rebound effect for different energy services in different sectors. This was the approach taken by Khazzoom (1980), who pointed to evidence that the long-run own-price elasticity of energy demand for water heating, space heating and cooking exceeded (minus) unity in some circumstances, implying that energy efficiency improvements for these services could lead to backfire (Taylor, *et al.*, 1977). However, reviews of this literature generally suggest that energy demand is inelastic in the majority of sectors in OECD countries (i.e.) (Dahl and Sterner, 1991; Dahl, 1993; 1994; Espey, 1998; Graham and Glaister, 2002; Hanley, *et al.*, 2002; Espey and Espey, 2004).

As an illustration, the upper bound for the direct rebound effect for personal automotive transport can be estimated from Hanley *et al.*'s (2002) meta-analysis¹⁶ of 51 empirical estimates of the long-run own-price elasticity of motor-fuel demand (E5). Taking the mean values,

16 A meta-analysis combines the results of several empirical studies that provide comparable quantitative estimates of a particular variable, such as the own-price elasticity of energy demand for a particular sector. In energy economics, a common approach is to use the estimated elasticities as the dependent variable in a multiple regression analysis that seeks to explain the variation in the results in terms of factors such as model structure (Bergh and Button, 1999).



this suggests an upper bound for the long-run direct rebound effect for this energy service of 64%.¹⁷ For comparison, three estimates of the elasticity of distance travelled by private cars with respect to the price of motor-fuel (E4) suggest a smaller long-run direct rebound effect of only 30% (Hanley, *et al.*, 2002). The difference between the two suggests that fuel prices have a significant influence on vehicle fuel efficiency over the long term and shows the extent to which the use of (E5) may lead to the direct rebound effect being overestimated.

For the purpose of estimating rebound effects, own-price elasticities for energy demand are most useful when the demand relates to a single energy service, such as refrigeration. They are less useful when (as is more common) the measured demand derives from a collection of energy services, such as household fuel or electricity consumption. In this case, a large own-price for fuel or electricity demand may suggest that improvements in the 'overall' efficiency of fuel or electricity use by the household will lead to large direct rebound effects (and vice versa). It may also suggest that the direct rebound effect for the energy services that dominate fuel or electricity consumption may be large. This is relevant for household heating, for example, since this typically accounts for more than two thirds of household fuel consumption. But many households use

more than one energy carrier for heating and there may also be scope for long-term substitution between different energy carriers. In these circumstances the own-price elasticity for fuel consumption could overestimate the own-price elasticity of fuel use for heating. At the same time, such aggregate data could underestimate the own-price elasticity of energy demand for other energy services. For example, it is possible that the energy demand for refrigeration is elastic – suggesting the possibility of large direct rebound effects – but if overall household electricity demand is inelastic, such a possibility is disguised.

Estimates of the own-price elasticity of household energy demand vary with the energy carrier, the type of household, the particular country and/or region, the level of household income¹⁸ and the methodological approach. For electricity, the results of a meta-analysis of more than 120 estimates suggests an upper bound for the short-term rebound effect for all household electricity services combined of 20-35% and an upper bound for the long-term effect of 80-85% (Espey and Espey, 2004). Evidence on fuel price elasticities is more variable and less robust, but generally suggests a lower price elasticity than for electricity (Baker and Blundell, 1991; Ferrer-i-Carbonell, *et al.*, 2002). Overall, and contrary to Khazzoom (1980), the evidence suggests that own-price elasticities of household fuel and electricity demand are less than

17 However, the mean values disguise a large variance in the results and using the full range of estimates suggests an upper bound of between 0 and 181%. This partly reflects the wide range of countries and time period on which the estimates are based. The corresponding mean value for the short run is 25%.

18 Price elasticities are frequently found to be higher among low income groups. For example, Baker *et al.* (1989) found that, conditional upon appliance ownership, the own-price elasticity of gas consumption by UK households was two times larger for the lowest income decile than for top income decile. However, Nesbakken (1999) found that the price elasticity of Norwegian household energy demand increases with income. Also, low income households often live in rented accommodation and hence have less scope for changing equipment such as heating systems over the long term (Poyer and Williams, 1992).



unity and hence that energy efficiency improvements are unlikely to lead to backfire (at least, not from direct rebound effects alone).

Whatever their origin, estimates of price elasticities should be treated with great caution. Aside from the difficulties of estimation, behavioural responses are contingent upon technical, institutional, policy and demographic factors that vary widely between different groups and over time. Demand responses are known to vary with the level of prices, the origin of price changes (e.g. exogenous versus policy induced), expectations of future prices, government fiscal policy (e.g. recycling of carbon tax revenues), saturation effects and other factors (Barker, *et al.*, 1995). The past is not necessarily a good guide to the future in this area, and it is possible that the very long-run response to price changes may exceed those found in empirical studies that rely upon data from relatively short time periods.

Instead of relying upon contested estimates of (E5), more accurate information on the magnitude of direct rebound effects may be obtained from studies that directly estimate (E3). However, data is only available on relevant measures of useful work for a subset of energy services. As a consequence, the reliable evidence base for the direct rebound effect is largely focused on personal automotive transportation, household heating and space cooling, where proxy measures of useful work are most readily available. These energy services form a significant component of household energy demand in OECD countries and may be expected

to be relatively price elastic. Econometric evidence for other consumer energy services is very limited, while that for producers is almost non-existent. The evidence base also exhibits a notable geographical bias, with the majority of studies referring to the United States and with very few studies of energy services in developing countries.

Our review of the empirical literature in this area is therefore largely confined to studies that estimate (E1), (E2) or (E3). These vary widely in terms of type of data, model structure, functional form and estimation techniques, which complicates the comparison of results. Given this diversity and the limited number of studies available we have not conducted a formal meta-analysis, but have instead summarised key results and identified possible sources of error. The result of this survey are summarised in the next two sections.

3.4 Direct rebound effects for private automotive transport

By far the best studied area for the direct rebound effect is personal transport by private car. Most studies refer to the US, which is important since fuel prices, fuel efficiencies and residential densities are lower than in Europe, car ownership levels are higher and there is less scope for switching to alternative transport modes.

Studies estimating (E1), (E2) or (E3) vary considerably in terms of the data used and specifications employed. Most studies use aggregate data which can capture



long-term effects on demand such as fuel efficiency standards, while household survey data can better describe individual behaviour at the micro level. Aggregate studies face numerous measurement difficulties, however, while disaggregate studies produce results that are more difficult to generalise. The relevant measure for useful work varies between total distance travelled, distance travelled per capita, distance travelled per licensed driver, distance travelled per household and distance travelled per vehicle.

Studies using aggregate time-series and cross-sectional data estimate the long-run direct rebound effect for personal automotive transport to be somewhere between **5% and 30%**. While there is disagreement over the appropriate specification the limited number of data points available makes it difficult to settle the issue from this type of data alone (Greene, 1992; Jones, 1993).¹⁹

Aggregate panel data²⁰ provides a more robust basis for estimates of the direct rebound effect, owing to the greater number of observations. Johansson and Schipper's (1997) cross-country study gives a best guess for the long-run direct rebound effect of **30%**, while both Houghton and Sakar (1996) and Small and van Dender (2005) converge on a long-run value of **22%** for the US. Small

and van Dender's study incorporates some important methodological innovations and is one of the few to test the hypothesis that the direct rebound effect declines with income (Box 3.2).

Studies using household survey data sources provide less consistent estimates of the direct rebound effect for personal automotive transport and several of these estimates are higher than those from aggregate data sources. Three US studies use data from the same source but produce estimates of the direct rebound effect that range from 0% to 87% (Goldberg, 1996; Puller and Greening, 1999; West, 2004).²¹ This diversity suggests that the results from disaggregate studies should be interpreted with more caution. One of the most rigorous studies using disaggregate data is by Greene *et al.* (1999), who estimate the US average long-run direct rebound effect to be **23%** - consistent with the results of studies using aggregate data.

Taken together, our review of 17 studies suggests that the long-run direct rebound effect for personal automotive transport lies somewhere between **10% and 30%**. The relative consensus on estimates, despite wide differences in data and methodologies suggests that the findings are relatively robust. Moreover, most of

19 The dispute relates to the appropriate treatment of serial correlation and lagged dependent variables. Serial correlation means that the error in one time period is correlated with the error from one or more previous time periods, perhaps as a result of the influence of unobserved variables that persist over time. Identifying and correcting for serial correlation is a major issue in time-series econometrics and is relevant to many studies of the direct rebound effect.

20 A pooled cross-section is a cross-sectional sample from a population, taken at two or more intervals in time. Panel data is similar, but with data from the same units in each sample period. An example would be data on motor-fuel consumption and related variables from each US state over a period 1972 to 2000.

21 All use the US Consumer Expenditure Survey, although covering different time periods and supplemented by differing sources of information on vehicle fuel efficiency. The figure of 87% is from West (2004) and is likely to be an overestimate of the direct rebound effect since it derives from the estimated elasticity of distance travelled with respect to operating costs, which includes maintenance and tyre costs.



these studies assume that the response to a change in fuel prices is equal in size to the response to a change in fuel efficiency, but opposite in sign. Few studies test this assumption explicitly and those that do are either unable to reject the hypothesis that the two elasticities are equal, or find that the fuel efficiency elasticity is *less* than the fuel cost per kilometer elasticity. The implication is that the direct rebound effect may lie towards the lower end of the above range.

The extent to which the direct rebound effect for personal automotive travel declines with income remains unclear, although the methodologically rigorous studies by Small and van Dender (2005) and Greene *et al.* (1999a) both suggest that it does. Measurement problems remain an issue for aggregate studies (Schipper, *et al.*, 1993), as does the geographical bias towards the United States. The available evidence is insufficient to determine whether direct rebound effects are larger or smaller in Europe, but it is notable that the meta-analysis by Espey (1998) found no significant difference in long-run own-price elasticities of gasoline demand. Overall, it must be concluded that direct rebound effects in this sector have not obviated the benefits of technical improvements in vehicle fuel efficiency. Between 70% to 100% of the potential benefits of such improvements appear to have been realised in reduced consumption of motor-fuels.

3.5 Direct rebound effects for other consumer energy services

The next best studied area for direct rebound effects is household heating, although relatively few studies estimate (E1), (E2) or (E3) for this energy service and even fewer investigate rebound effects specifically. The available studies rely upon detailed household survey data and exhibit even greater diversity in terms of the variables measured and the methodologies adopted. Four of the most rigorous studies are briefly described here.

Schwarz and Taylor (1995) use cross-sectional data from 1188 single family US households, including measurements of thermostat settings. They estimate an equation for the thermostat setting as a function of energy prices, external temperature, heated area, household income and an engineering estimate of the thermal resistance of the house. Their data also allows them to estimate the demand for useful work for space heating. On the basis of thermostat settings, their estimate of (E2) suggests a long-run direct rebound effect of 0.6% to 2.0%, while on the basis of the demand for useful work their estimate suggests a larger effect of 1.4% to 3.4%. While these estimates are smaller than those from other studies, the difference between the two is comparable to that between behavioural responses and temperature take-back identified by the evaluation studies.

Hseuh and Gerner (1993) use comparable data from 1281 single family detached



Box 3.2 The declining direct rebound effect

Small and van Dender (2005) provide one of the most methodologically rigorous estimates of the direct rebound effect for personal automotive transport. They estimate an econometric model explaining the amount of travel by passenger cars as a function of the cost per mile and other variables. By employing simultaneous equations for vehicle numbers, average fuel efficiency and vehicle miles travelled, they are able allow for the fact that fuel efficiency is endogenous: i.e. more fuel-efficient cars may encourage more driving, while the expectation of more driving may encourage the purchase of more fuel-efficient cars. Their results show that failing to allow for this can lead the direct rebound effect to be substantially overestimated.

Small and Van Dender use aggregate data on vehicle numbers, fuel efficiency, gasoline consumption, vehicle miles travelled and other variables for 50 US states and the District of Columbia covering the period 1961 to 2001. This approach provides considerably more observations than conventional aggregate time-series data, while at the same time providing more information on effects that are of interest to policymakers than do studies using household survey data. The effect of the CAFE standards on vehicle fuel efficiency are estimated by incorporating a variable representing the gap between the fuel efficiency standard and an estimate of the efficiency that would have been chosen in the absence of the standards, giving prevailing fuel prices.

Small and Van Dender estimate the short-run direct rebound effect for the US as a whole to be 4.5% and the long-run effect to be 22%. The former is lower than most of the estimates in the literature, while the latter is close to the consensus. However, they estimate that a 10% increase in income reduces the short-run direct rebound effect by 0.58%. Using US average values of income, urbanisation and fuel prices over the period 1997-2001, they find a direct rebound effect of only 2.2% in the short-term and 10.7% in the long-term - approximately half the values estimated from the full data set. If this result is robust, it has some important implications. However, two-fifths of the estimated reduction in the rebound effect derives from the assumption that the magnitude of this effect depends upon the absolute level of fuel costs per kilometre. But since the relevant coefficient is not statistically significant, this claim is questionable.

Although methodologically sophisticated, the study is not without its problems. Despite covering 50 states over a period of 36 years, the data provides relatively little variation in vehicle fuel efficiency making it difficult to determine its effect separately from that of fuel prices. Direct estimates of (E2) are small and statistically insignificant, which could be interpreted as implying that the direct rebound effect is approximately zero, but since this specification performs rather poorly overall, estimates based upon (E3) are preferred. Also, the model leads to the unlikely result that the direct rebound effect is negative some states (Harrison, *et al.*, 2005). This raises questions about the use of the model for projecting declining rebound effects in the future, since increasing incomes could make the estimated direct rebound effect negative in many states.



households in the US, dating back to 1981. Their dataset includes comprehensive information on appliance ownership and demographic characteristics, which allows them to combine econometric and engineering models to estimate the energy use for space heating. On the basis of an estimate of (E5), conditional on the existing level of energy efficiency, the short-run direct rebound effect can be estimated as 35% for electrically heated homes and 58% for gas heated homes.

Klein (1987; 1988) uses comparable data from more than 2000 US households, supplemented with an engineering model of the thermal performance of buildings and data on the capital cost of equipment. This allows the estimation of a sophisticated 'household production' model, involving simultaneous equations for the total cost of space heat, the share of energy in the total cost of space heat and the demand for space heat. On the basis of (E3), Klein's model suggests a short-run direct rebound effect in the range 25% to 29%.²²

Guertin *et al.* (2003) use detailed survey data from 440 single family Canadian households and apply 'frontier analysis' to estimate the energy efficiency of the relevant appliances. This in turn allows the energy consumption for space heating, water heating and appliances/lighting to be estimated. On the basis of (E3), Guertin *et al.*'s model suggests a long-run mean rebound effect

of 38%, varying from 29% for high income groups to 47% for low income groups.²³

Other estimates of direct rebound effects for household heating include Haas and Biermayer (2000) who use a variety of techniques to reach an estimate of 15-30% for German households, and Douthitt (1986) whose study of 370 Canadian households suggest short-run effects in the range 10-17% and long-run effects in the range 25-60%.

Reliable estimates of the direct rebound effects for household heating therefore range from **10% to 58%** in the short-run and **1.4% to 60%** in the long-run, with a suggestion that rebound effects are larger for low income groups. As with the evaluation studies, the definition of the direct rebound effect is not consistent between the above studies, the response varies between different households and the results from one time period and geographical area may not translate to other circumstances. Nevertheless, for the purpose of policy evaluation, a figure of **30%** for the direct rebound effect for household heating would appear a reasonable assumption.

For space cooling in households, two studies provide estimates of direct rebound effects that are within the range of those reported for space heating (i.e. **1-26%**) (Hausman, 1979; Dubin, *et al.*, 1986). However, these relatively old studies use small sample sizes and were conducted during period of rising energy

22 Greening *et al.*' (1998) quote a figure of 40% from the study, but this overestimates the direct rebound effect since it is based upon the elasticity of heat demand with respect to the generalised cost of space heat, which includes capital and maintenance costs.

23 The variation in (E3) between income groups was much greater for space heating than for other energy services.



prices. Their results may not be transferable to many European countries, given the differences in house types and climatological conditions. Also, both studies focus solely upon changes in equipment utilisation. To the extent that ownership of space cooling technology is rapidly increasing in many countries, demand from 'marginal consumers' may be an important consideration, together

with increases in system capacity among existing users.

Evidence for water heating is also very limited, although Guertin *et al.* (2003) provides estimates in the range 34 to 38%, which is greater than the results from US evaluation studies reported by Nadel (1993). A methodologically rigorous study of direct rebound effects for clothes washing suggests that direct rebound

Box 3.3 Direct rebound effects for clothes washing

Davis (2007) provides a unique example of an estimate of direct rebound effects for household clothes washing - which together with clothes drying accounts for around one tenth of household energy consumption. The estimate is based upon a US government-sponsored field trial of high-efficiency washing machines involving 98 participants. These machines use 48% less energy per wash than standard machines and 41% less water.

While participation in the trial was voluntary, both the utilisation of existing machines and the associated consumption of energy and water was monitored for a period of two months prior to the installation of the new machine. This allowed household specific variations in utilisation patterns to be controlled for and permitted unbiased estimates to be made of the price elasticity of machine utilisation.

The monitoring allowed the marginal cost of clothes washing for each household to be estimated. This was then used as the primary independent variable in an equation for the demand for clean clothes in kg/day (useful work). Davis found that the demand for clean clothes increased by 5.6% after receiving the new washers, largely as a result of increases in the weight of clothes washed per cycle rather than the number of cycles. While this could be used as an estimate of the direct rebound effect, it results in part from savings in water and detergent costs. If the estimate was based solely on the savings in energy costs, the estimated effect would be smaller. This suggests that only a small portion of the gains from energy efficient washing machines will be offset by increased utilisation.

Davis estimates that time costs form 80-90% of the total cost of washing clothes. The results therefore support the theoretical prediction that, for time intensive activities, even relatively large changes in energy efficiency should have little impact on demand. Similar conclusions should therefore apply to other time-intensive energy services that are both produced and consumed by households, including those provided by dishwashers, vacuum cleaners, televisions, power tools, computers and printers.



effects for 'minor' energy services should be relatively small (Box 3.3). However, this confines attention to households that already have automatic washing machines and therefore excludes rebound effects from marginal consumers.

Table 3.1 summarises the results of our survey of econometric estimates of the direct rebound effect. Despite the methodological diversity, the results for individual energy services are broadly comparable. This suggests that the evidence for direct rebound effects is relatively robust to different datasets and methodologies.

These relatively modest estimates for direct rebound effects are based upon studies in OECD countries and are unlikely to be representative of conditions in developing countries. Hence, two studies from developing countries deserve a mention. In a rare study of traditional fuels, Zein-Elabdin (1997) estimates direct rebound effects from fuel-efficient stoves in Khartoum by multiplying the fuel efficiency improvement by the product of the estimated income elasticity of demand for charcoal and the share of charcoal in the household budget. Allowing for the

additional (indirect) effects on the price of charcoal leads to an estimated rebound effect of 42%.

Roy (2000) reports the results of a government programme that freely distributed solar-charged battery lamps to a rural village in India. These lamps provided significantly better lighting quality than the kerosene lamps they displaced. Daily hours of lighting increased from two to four, provided by a combination of new and old lamps since the solar lamps were limited in operating hours. This led to a direct rebound effect of approximately 50% (80% for some households). Moreover, since the 'saved' kerosene was either used for cooking or sold, accounting for indirect effects suggests that the programme achieved no energy savings - although significant benefits to welfare. Since the lamps were free and kerosene subsidised, this may be an atypical example. However, the primary source of the large rebound effect was the large unsatisfied demand for lighting. This condition applies to a range of energy services in developing countries and especially for the 1.6 billion households who currently lack access to

Table 3.1 Estimates of the long-run direct rebound effect for consumer energy services in the OECD

End-Use	Range of Values in Evidence Base	'Best guess'	No. of Studies	Degree of Confidence
Personal automotive transport	5-87%	10-30%	17	High
Space heating	1.4-60%	10-30%	9	Medium
Space cooling	1-26%	1-26%	2	Low
Other consumer energy services	0-49%	<20%	3	Low



electricity and the 2.5 billion who rely upon biomass for cooking.

3.6 Sources of bias in estimates of the direct rebound effect

The use of price elasticities to estimate the direct rebound effect creates the risk of bias. Most studies assume that changes in energy prices have an opposite effect to comparable changes in energy efficiency and that any changes in energy efficiency derive solely from outside the model (i.e. energy efficiency is 'exogenous'). In practice, both of these assumptions may be incorrect.

First, while changes in energy prices are generally not correlated with changes in other input costs, changes in energy efficiency may be. In particular, higher energy efficiency may only be achieved through the purchase of new equipment with higher capital costs than less efficient models. Hence, estimates of the direct rebound effect that rely primarily upon historical and/or cross-sectional variations in energy prices could overestimate the direct rebound effect, since the additional capital costs required to improve energy efficiency will not be taken into account (Henly, *et al.*, 1988).

Second, energy price elasticities tend to be higher for periods with rising prices than for those with falling prices (Gately, 1992; 1993; Dargay and Gately, 1994; 1995; Haas and Schipper, 1998). For example, Dargay (1992) found that the reduction in UK energy demand following the price rises of the late 1970s was five

times greater than the increase in demand following the price collapse of the mid-1980s. An explanation may be that higher energy prices induce technological improvements in energy efficiency, which may also become embodied in regulations (Grubb, 1995). Also, investment in measures such as thermal insulation is largely irreversible over the short to medium-term. But the appropriate proxy for improvements in energy efficiency is *reductions* in energy prices. Since many studies based upon time series data incorporate periods of rising energy prices, the estimated price elasticities may overestimate the response to falling energy prices. As a result, such studies could overestimate the direct rebound effect.

Third, while improved energy efficiency may increase the demand for useful work (e.g. you could drive further after purchasing an energy-efficient car), it is also possible that the anticipated high demand for useful work may increase the demand for energy efficiency (e.g. you purchase an energy-efficient car because you expect to drive further). In these circumstances, the demand for useful work depends on the price of useful work, which depends upon energy efficiency, which depends upon the demand for useful work (Small and Van Dender, 2005). Hence, the direct rebound effect would not be the only explanation for any measured correlation between energy efficiency and the demand for useful work. This so-called 'endogeneity' can be addressed through the use of simultaneous equation models, but these are relatively uncommon owing to their greater data requirements. If, instead,



studies include the 'endogenous' variable(s) within a single equation and do not use appropriate techniques to estimate this equation, the resulting estimates could be biased. Several studies of direct rebound effects could be flawed for this reason.

Finally, consumers may be expected to take the full costs of energy services into account when making decisions about the consumption of those services and these include the *time* costs associated with producing and/or using the relevant service - for example, the time required to travel from A to B. Indeed, the increase in energy consumption in industrial societies over the past century may have been driven in part by attempts to 'save time' (and hence time costs) through the use of technologies that allow tasks to be completed faster at the expense of using more energy. For example, travel by private car has replaced walking, cycling and public transport; automatic washing machines have replaced washing by hand; fast food and ready meals have replaced traditional cooking and so on. While not all energy services involve such trade-offs, many do (compare rail and air travel for example). Time costs may be approximated by hourly wage rates and since these have risen more rapidly than energy prices throughout the last century, there has been a strong incentive to substitute energy for time (Becker, 1965). If time costs continue to increase in importance relative to energy costs, the direct rebound effect for many energy services should become *less* important –

since improvements in energy efficiency will have an increasingly small impact on the total cost of useful work (Binswanger, 2001). This suggests that estimates of the direct rebound effect that do not control for increases in time costs (which is correlated with increases in income) could potentially overestimate the direct rebound effect. Box 3.2 shows how this could be particularly relevant to direct rebound effects in transport.

The consideration of time costs also points to an important but relatively unexplored issue: increasing time efficiency may lead to a parallel 'rebound effect with respect to time' (Binswanger, 2001; Jalas, 2002). For example, faster modes of transport may encourage longer commuting distances, with the time spent commuting remaining broadly unchanged.²⁴ So in some circumstances energy consumption may be increased, first, by trading off energy efficiency for time efficiency (e.g. choosing air travel rather than rail) and second, by the rebound effects with respect to time (e.g. choosing to travel further).

3.7 Summary

- Evidence for the direct rebound effect for automotive transport and household heating within developed countries is relatively robust. Evidence for direct rebound effects for other consumer energy services is much weaker, as is that for energy efficiency improvements by

²⁴ In the UK, the time spent travelling increased by only 17% between 1975 and 2005, while the total distance travelled increased by 52% (Department of Transport, 2006).



producers. Evidence is particularly weak for energy efficiency improvements in developing countries although theoretical considerations suggest that direct rebound effects in this context will be larger than those in developed countries.

- Under certain assumptions, estimates of the own-price elasticity of energy demand for an individual energy service should provide an upper bound for the direct rebound effect for that service. If the measured energy demand relates to a group of energy services (e.g. household fuel demand), the own price elasticity should provide an approximate upper bound for the weighted average of direct rebound effects for those services. Since the demand for energy is generally found to be inelastic in OECD countries, the long-run direct rebound effect for most energy services should be less than 100%.
- For personal automotive transport, household heating and household cooling in OECD countries, the mean value of the direct rebound effect is likely to be less than 30% and may be closer to 10% for transport. Moreover, the direct rebound effect is expected to decline in the future as demand saturates and income increases. Both theoretical considerations and the available empirical evidence suggest that direct rebound effects should be smaller for other consumer energy services where energy forms a small proportion of total costs. Hence, at least for OECD countries, direct rebound effects should only partially offset the energy savings from energy efficiency improvements in consumer energy services.
- These conclusions are subject to a number of qualifications, including the relatively limited time periods over which direct rebound effects have been studied and the restrictive definitions of 'useful work' that have been employed. For example, current studies only measure the increase in distance driven for automotive transport and do not measure changes in vehicle size. Rebound effects for space heating and other energy services are also higher among low income groups and most studies do not account for 'marginal consumers' acquiring services such as space cooling for the first time.
- The methodological quality of many 'evaluation studies' is poor, while the estimates from many econometric studies appear vulnerable to bias. The most likely effect of the latter is to lead the direct rebound effect to be overestimated. Considerable scope exists for improving estimates of the direct rebound effect for the energy services studied here and for extending estimates to include other energy services.



4. The evidence for indirect and economy-wide rebound effects

This section summarises the empirical evidence for indirect and economy-wide rebound effects, focusing upon the limited number of studies that provide quantitative estimates of these effects. This is separate from the more 'indirect' evidence for economy-wide rebound effects that is the subject of Section 5. A full examination of this evidence is contained in *Technical Report 4* and *Technical Report 5*.

Indirect rebound effects derive from two sources: the energy required to produce and install the measures that improve energy efficiency, such as thermal insulation, and the indirect energy consumption that results from such improvements. The first of these relates to energy consumption that occurs prior to the energy efficiency improvement, while the second relates to energy consumption that follows the improvement. Sections 4.1 and 4.2 describe the mechanisms responsible for each.

Section 4.3 examines the limited empirical evidence for indirect rebound effects, focusing on studies that estimate the 'embodied' energy associated with different categories of consumer goods and services. Despite the apparent potential of this approach, there appear to be very few applications to the rebound effect.

Section 4.4 examines the evidence for economy-wide rebound effects available from computable general equilibrium (CGE) models of the macro-economy. These simulate the full range of mechanisms responsible for rebound effects, but the realism and policy

relevance of this approach is open to question. Also, despite the widespread use of such models, there are only a handful of applications to the rebound effect. Section 4.5 describes an alternative 'macro-econometric' approach that can overcome some of these weaknesses, and summarises the results of a recent application of this approach to the UK economy. Section 4.6 concludes.

4.1 Embodied energy – the limits to substitution

Many improvements in energy efficiency can be understood as the 'substitution' of capital for energy within a particular system boundary. For example, thermal insulation (capital) may be substituted for fuel (energy) to maintain the internal temperature of a building at a particular level. It is these possibilities that form the basis of estimated 'energy saving' potentials in different sectors. However, estimates of energy savings typically neglect the energy consumption that is required to produce and maintain the relevant capital - frequently referred to as *embodied energy*. For example, energy is required to produce and install home insulation materials and energy efficient motors. Substituting capital for energy therefore shifts energy use from the sector in which it is used to sectors of the economy that produce that capital. As a result, energy use may increase elsewhere in the economy (Kaufmann and Azary-Lee, 1990).

Figure 4.1 provides a graphical interpretation of this process (Stern, 1997). Here, the function $F(K)$ represents

the different combinations of energy (E) and capital (K) that may be used to provide a given level of output for a particular firm or sector. But this capital also has indirect energy consumption associated with it, elsewhere in the economy, represented by the function $G(K)$. The summation of the two gives the total energy $H(K)$ used in the economy as a whole to produce the given level of output. It can be seen that: first, the net energy savings from the substitution of capital for energy will be less than the energy savings within the firm or sector in which the substitution takes place; and second, when capital inputs exceed a certain level (K'), the indirect energy consumption will exceed the direct energy savings – leading to backfire for the economy as a whole, even when the individual firm or sector reduces energy consumption and when output from this sector is unchanged.

In practice, backfire from this source alone appears rather unlikely, since the cost of an energy efficient technology should reflect the cost of the embodied energy (Webb and Pearce, 1975). If the latter exceeds the saving in energy costs, it is unlikely that the investment would be cost-effective.²⁵ However, this assumes that the sole benefit of the investment is

the reduced energy costs, which may not always be the case. Also, market imperfections may distort the relevant prices and costs.

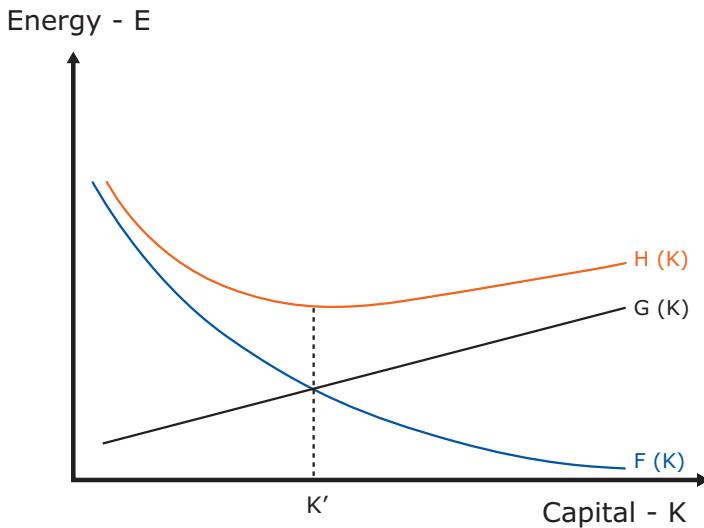
In contrast to other sources of the economy-wide rebound effect, the contribution from this source may be expected to be smaller in the long-term than in the short-term. This is because the embodied energy associated with capital equipment is analogous to a capital cost and hence diminishes in importance relative to ongoing energy savings as the lifetime of the investment increases.

Some authors argue that similar conclusions apply to the substitution of labour for energy, since energy is also required to feed and house workers and thereby keep them economically productive (Kaufmann, 1992). However, there is some dispute over whether and how to account for the 'energy cost of labour' (Costanza, 1980).²⁶ Similarly, while economists conventionally distinguish between substitution and technical change (Box 2.1), the latter is also associated with indirect energy consumption since it is embodied in capital goods and skilled workers (Stern and Cleveland, 2004).

25 Note that this argument applies to measures of energy consumption weighted by the relative price of different energy carriers and not to energy consumption measured simply in terms of heat content.

26 Costanza (1980) estimates the energy cost of labour as the energy associated with all personal consumption expenditures. These energy costs are then assigned to individual goods and services in proportion to the labour required to produce them. Double counting is avoided by changing the boundaries of the traditional economic input-output analysis. The net result is to greatly increase the embodied energy estimated to be associated with labour-intensive goods and services. With this approach, the 'embodied energy intensity' of most sectors (excluding primary energy) is found to be broadly comparable. However, this conclusion depends entirely upon the particular methodology for calculating the energy cost of labour. This is quite different from conventional accounting approaches, which estimate much lower energy intensities for many sectors and greater variation between them. It also implicitly assumes that all personal consumption expenditures are necessary to support labour, which appears unjustified.

Figure 4.1 The limits to substitution Source: Stern (1997)



In principle, an assessment of the embodied energy associated with a particular energy efficiency improvement should take into account the relevant alternatives. For example, a mandatory requirement to replace existing refrigerators with more energy efficient models may either increase or decrease aggregate energy consumption over a particular period of time, depending upon the age of the existing stock, the lifetime of the new stock, and the direct and indirect energy consumption associated with different models of refrigerator. In practice, however, such estimates appear to be rare, with most analysts focusing instead upon the 'energy return on energy invested'²⁷ for different energy supply options (Cleveland, 1992).²⁸

4.2 Secondary effects

Energy efficiency improvements may themselves change the demand for other goods and services. For example, the purchase of a more fuel-efficient car may reduce demand for public transport, but at the same time increase the demand for leisure activities that can only be accessed with a private car (Binswanger, 2001). Each of these goods and services will have an indirect energy consumption associated with them and the changed pattern of demand may either increase overall energy consumption or reduce it. The net impact of such effects will be specific to both individual technologies and individual consumers and can also be very difficult to estimate.

²⁷ The Energy Returned on Energy Invested (EroEI) is the ratio of the usable energy acquired from a particular energy resource to the amount of energy expended to obtain that energy resource. In principle, when the EROEI of a resource is equal to or lower than 1, that energy source can no longer be used as a primary source of energy. However, this measure neglects the relative economic productivity of different energy forms. When this is taken into account, resources with an EroEI of less than unity may still be economic to extract.

²⁸ Studies based upon embodied energy have fallen out of favour since the 1980s, when they were often associated with somewhat controversial 'energy theories of value' (Söllner, 1997). But there is no necessary link between these theories and use of 'embodied energy' estimates in empirical research. Consideration of rebound effects may provide a motivation for reviving this area of research.

Very similar effects will result from energy efficiency improvements by producers. For example, energy efficiency improvements in steel production should reduce the cost of steel and (assuming these cost reductions are passed on in lower product prices)²⁹ reduce the input costs of manufacturers that use steel. This in turn should reduce the cost of steel products and increase demand for those products. Such improvements could, for example, lower the cost of passenger cars, increase the demand for car travel and thereby increase demand for motor-fuel.

This example demonstrates how energy efficiency improvements could lead to a series of adjustments in the prices and quantities of goods and services supplied throughout an economy. If the energy efficiency improvements are widespread, the price of energy intensive goods and services may fall to a greater extent than that of non-energy intensive goods and services, thereby encouraging consumer demand to shift towards the former. If energy demand is reduced, the resulting fall in energy prices will encourage greater energy consumption by producers and consumers and will feed through into lower product prices, thereby encouraging further shifts towards energy intensive commodities. Reductions in both energy prices and product prices will increase consumers' real income, thereby increasing demand for products,

encouraging investment, stimulating economic growth and further stimulating the demand for energy. In some circumstances, such improvements could also change trade patterns and international energy prices and therefore impact on energy consumption in other countries.

A number of analysts have claimed that the secondary effects from energy efficiency improvements in consumer technologies are relatively small (Lovins, *et al.*, 1988; Greening and Greene, 1998; Schipper and Grubb, 2000). This is because energy makes up a small share of total consumer expenditure and the energy content of most other goods and services is also small. For example, suppose energy efficiency improvements reduce natural gas consumption per unit of space heated by 10%. If there is no direct rebound effect, consumers will reduce expenditure on natural gas for space heating by 10%. If natural gas for heating accounts for 5% of total consumer expenditure, consumers will experience a 0.5% increase in their real disposable income. If *all* of this were spent on motor-fuel for additional car travel, the net energy savings (in kWh thermal content) will depend upon the ratio of natural gas prices to motor-fuel prices, and could in principle be more or less than one.³⁰ In practice, however, motor-fuel only accounts for a portion of the total cost of car travel and car travel

29 Product prices will only fall if a sufficiently large number of domestic firms within the sector benefit from the energy efficiency improvement and will be limited by the extent to which the product market is exposed to international competition.

30 Chalkley *et al.* (2001) provide an example of the replacement of an inefficient (C-rated) refrigerator with an efficient (A-rated) model. Lifetime carbon savings for the refrigerator are estimated at 1645 kgCO₂ and lifetime cost savings at £120.57. If these cost savings were spent wholly on gasoline, the indirect CO₂ emissions would be 358 kg, giving an indirect rebound effect, in carbon terms, of 22%. However, spending all of the cost savings on gasoline is unrealistic.

only accounts for a portion of total consumer expenditure. For the great majority of goods and services, input-output data suggests that the effective expenditure on energy should be less than 15% of the total expenditure. Hence, by this logic, the secondary effect should be only around one tenth of the direct effect (Greening and Greene, 1998).

Entirely analogous arguments apply to the secondary effects for producers, such as in the steel example above. Since energy forms a small share of total production costs for most firms and sectors (typically <3%) and since intermediate goods form a small share of the total costs of most final products, the product of these suggests an indirect effect that is much smaller than the direct effect (Greening and Greene, 1998).

However, while plausible, these arguments are not supported by the results of several of the quantitative studies discussed below. Moreover, they assume that the only effect of the energy efficiency improvement is to reduce expenditure on energy. But as argued in Section 2, improvements in the energy efficiency of production processes are frequently associated with improvements in the productivity of capital and labour as well and therefore lead to cost savings that exceed the savings in energy costs alone. In some cases, similar arguments may apply to energy efficiency improvements by consumers: for example, a shift from car travel to cycling could save on depreciation and maintenance costs for vehicles as well as motor-fuel costs (Alfredsson, 2004). In these circumstances, the secondary effects that result from the adoption of a

particular technology could be substantial and may even exceed the direct energy savings.

4.3 Evidence for limits to substitution

Some indication of the importance of embodied energy may be obtained from estimates of the own-price elasticity of *aggregate* primary, secondary or final energy demand. In principle, this measures the scope for substituting capital, labour and materials for energy, while holding output constant. Most energy price elasticities are estimated at the level of individual sectors and therefore do not reflect all the embodied energy associated with capital, labour and materials inputs. Since the own-price elasticity of aggregate energy reflects this indirect energy consumption, it should in principle be smaller than a weighted average of energy demand elasticities within each sector. However, the aggregate elasticity may also reflect price-induced changes in economic structure and product mix which in principle could make it larger than the average of sectoral elasticities (Sweeney, 1984). These two mechanisms therefore act in opposition.

Based in part upon modelling studies, Sweeney (1984) puts the long-run elasticity of demand for primary energy in the range -0.25 to -0.6. In contrast, Kaufmann (1992) uses econometric analysis to propose a range from -0.05 to -0.39, while Hong (1983) estimates a value of -0.05 for the US economy. A low value for this elasticity may indicate a

limited scope for substitution and hence the potential for large indirect rebound effects.³¹ But this interpretation is not straightforward, since direct rebound effects also contribute to the behaviour being measured. Also, measures of the quantity and price of 'aggregate energy' are sensitive to the methods chosen for aggregating the prices and quantities of individual energy carriers, while the price elasticity will also depend upon the particular composition of price changes (e.g. increases in oil prices relative to gas) (EMF 4 Working Group, 1981). In particular, when different energy types are weighted by their relative marginal productivity, the estimated elasticities tend to be lower (Hong, 1983) As a result, the available estimates of aggregate price elasticities may be insufficiently precise to provide much indication of the magnitude of indirect rebound effects.

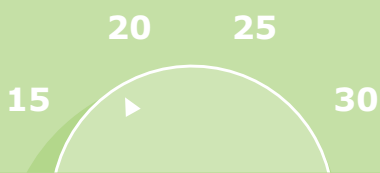
Relatively few empirical studies have investigated the embodied energy associated with specific energy efficiency improvements and those that have appear to focus disproportionately upon domestic buildings. In a rare study of energy efficiency improvements by producers, Kaufmann and Azary Lee (1990) estimate that, in the US forest products industry over the period 1954 to 1984, the embodied energy associated with capital equipment offset the direct energy savings from that equipment by as much

as 83% (Box 4.1). But since their methodology is crude and the results specific to the US context, this study provides little indication of the magnitude of these effects more generally.

Estimates of the embodied energy of different categories of goods and services can be obtained from input-output analysis, life-cycle analysis (LCA) or a combination of the two (Chapman, 1974; Herendeen and Tanak, 1976; Kok, *et al.*, 2006). A full life-cycle analysis is time consuming to conduct and must address problems of 'truncation' (i.e. uncertainty over the appropriate system boundary)³² and joint production (i.e. how to attribute energy consumption to two or more products from a single sector) (Leach, 1975; Lenzen and Dey, 2000). Hence, many studies combine standard economic input-output tables with additional information on the energy consumption of individual sectors, to give a comprehensive and reasonably accurate representation of the direct and indirect energy required to produce rather aggregate categories of goods and services. More detailed, LCA-based estimates are available for individual products such as building materials, but results vary widely from one context to another depending upon factors such as the fuel mix for primary energy supply (Sartori and Hestnes, 2007).

31 This is in contrast to the own-price elasticity of energy demand for an individual energy service, where high values may indicate the potential for large direct rebound effects.

32 For example, should the indirect energy costs of a building also include the energy used to make the structural steel and mine the iron ore used to make the girders? This is referred to as the truncation problem because there is no standard procedure for determining when energy costs become small enough to neglect

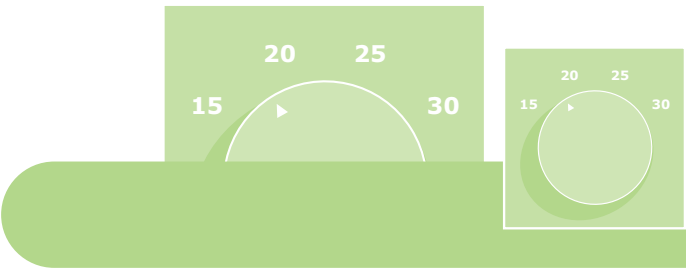


Box 4.1 Limits to substitution for producers

Kaufmann and Azary Lee (1990) examined the embodied energy associated with energy efficiency improvements in the US forest products industry over the period 1954 to 1984. First, they estimated a production function for the output of this industry and used this to derive the 'marginal rate of technical substitution' (MRTS) between capital and energy in a given year - in other words, the amount of gross fixed capital that was used to substitute for a thermal unit of energy in that year. Second, they approximated the embodied energy associated with that capital by means of the aggregate energy/GDP ratio for the US economy in that year - hence ignoring the particular type of capital used, as well as the difference between the energy intensity of the capital producing sectors and that of the economy as a whole. The product of these two variables gave an estimate of the indirect energy consumption associated with the gross capital stock used to substitute for a unit of energy. This was then multiplied by a depreciation rate to give the energy associated with the capital services used to substitute for a unit of energy.

Finally, they compared the estimated indirect energy consumption with the direct energy savings in the forest products sector in each year. Their results showed that the indirect energy consumption of capital offset the direct savings by between 18 and 83% over the period in question, with the net energy savings generally decreasing over time. The primary source of the variation was the increase in the MRTS over time, implying that an increasing amount of capital was being used to substitute for a unit of energy. However, the results were also influenced by the high energy/GDP ratio of the US economy, which is approximately twice that of many European countries. Overall, the calculations suggest that the substitution reduced aggregate US energy consumption, but by much less than a sector-based analysis would suggest. Also, their approach did not take into account any secondary effects resulting from the energy efficiency improvements.

The simplicity of this approach suggests the scope for further development and wider application. Accuracy could be considerably improved by the use of more flexible production functions and more precise estimates for the indirect energy consumption associated with specific types and vintages of capital goods. However, to date no other authors appear to have applied this approach to particular industrial sectors or to have related it to the broader debate on the rebound effect.



As an illustration, Sartori and Hestnes (2007) reviewed 60 case studies of buildings, and found that the share of embodied energy in life-cycle energy consumption ranged between 9 and 46% for low energy buildings and between 2 and 38% for conventional buildings – with the wide range reflecting different building types, material choices and climatic conditions. Two studies that controlled for these variables found that low energy designs could achieve substantial reductions in operating energy consumption with relatively small increases in embodied energy, leading to ‘payback periods’ for energy saving of as little as one year (Feist, 1996; Winther and Hestnes, 1999). Similar calculations were performed by the Royal Commission on Environmental Pollution (2007), who estimate a 15 year simple payback (in energy terms) for low energy new build houses in the UK. However, Casals (2006) shows how the embodied energy of such buildings could offset operational energy savings, even with an assumed 100 year lifetime. Such calculations typically neglect differences in energy quality and the results are sensitive to context, design and building type. However, the increasing availability of embodied energy coefficients at a national level (e.g. Alcorn and Baird (1996)) suggests the scope for greater use of such estimates in policy evaluation.

In the case of existing buildings, several studies suggest that retrofits of thermal insulation pay for themselves in terms of energy savings within a few months (compared to a useful life in excess of 25

years), while the corresponding period for double glazing is several years. In other cases, for example condensing boilers compared to conventional boilers, the variation of embodied energy within individual categories of boiler exceeds the difference between them. Hence, the contribution of embodied energy to the economy-wide rebound effect appears to vary widely from one situation to another and is inversely proportional to the lifetime of the energy saving measure. But the patchy nature of this evidence base, the lack of systematic comparisons of energy efficiency options and the dependence of the results on particular contexts all make it difficult to draw any general conclusions.

4.4 Evidence for secondary effects

By combining estimates of the embodied energy associated with different categories of goods and services with survey data on household consumption patterns, it is possible to estimate the total (direct plus indirect) energy consumption of different types of household; together with the indirect energy consumption associated with particular categories of expenditure (Kok, *et al.*, 2006). It is often found that the indirect energy consumption of households exceeds the direct consumption. Moreover, while indirect energy consumption increases with income, direct energy consumption shows signs of saturation - suggesting that

indirect energy consumption is becoming increasingly important over time.³³

If this data is available at a sufficiently disaggregated level, it could also be used to estimate the secondary effects associated with energy efficiency improvements by households - provided that additional information is available on either the cross price elasticity between different product and service categories, or the marginal propensity to spend³⁴ of different income groups. By combining the estimates of embodied energy and secondary effects, an estimate of the total indirect rebound effect may be obtained. Such approaches are 'static' in that they do not capture the full range of price and quantity adjustments, but could nevertheless be informative.³⁵ However, of the 19 studies in this area reviewed by Kok, *et al.* (2006), only three were considered to have sufficient detail to allow the investigation of such micro-level changes - largely because they combined input-output with LCA data (Bullard, *et al.*, 1978). Hence, estimation of secondary effects by this route appears to be in its infancy.

Three studies that use this general approach are summarised here. First, Brännlund *et al.* (2007) examine the

effect of a 20% improvement in the energy efficiency of personal transport (all modes) and space heating in Sweden. They estimate an econometric model of aggregate household expenditure, in which the share of total expenditure for thirteen types of good or service is expressed as a function of the total budget, the price of each good or service and an overall price index. This allows the own-price, cross-price and income elasticities of each good or service to be estimated.³⁶ Energy efficiency improvements reduce the cost of transport and heating and lead to substitution and income effects that change overall demand patterns (e.g. improvements in transport efficiency are estimated to increase demand for clothes but to decrease demand for beverages). By combining these estimated changes in demand patterns with CO₂ emission coefficients for each category of good and service (based upon estimates of direct and indirect energy consumption) Brännlund *et al.* find that energy efficiency improvements in transport and heating lead to (direct + indirect) rebound effects (in carbon terms) of 120% and 170% respectively.

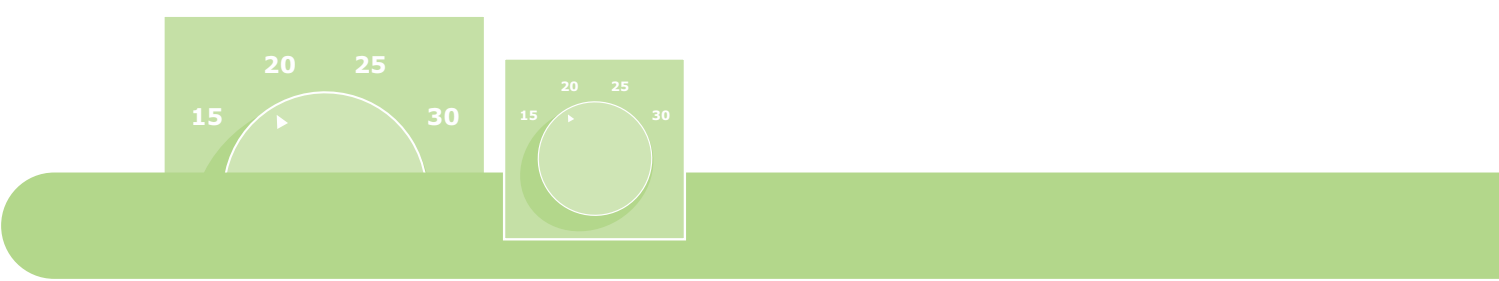
Brännlund *et al.*'s results are heavily dependent on the assumed carbon

33 Results vary widely with country, time period and methodology. For example, Herendeen (1978) found that indirect energy consumption in Norway accounted for one third of total energy consumption for a poor family and approximately two thirds for a rich family. Vringer and Blok (1995) found that 54% of total energy demand in Dutch households was indirect, while Lenzen (1998) found that 30% of total energy demand in Australian households was indirect.

34 Defined as the change in expenditure on a particular product or service, divided by the change in total expenditure. The marginal propensity to spend on different goods and services varies with income and it is an empirical question as to whether the associated indirect energy consumption is larger or smaller at higher levels of income. However, the greater use of energy intensive travel options by high income groups (notably flying) could be significant in some cases.

35 In technical terms, these provide a partial equilibrium analysis, as distinct from the general equilibrium analysis provided by CGE models.

36 Brännlund *et al.* employ Almost Ideal Demand (AID) model, which has been shown to have a number of advantages over other models of consumer demand (Deaton and Mulbauer, 1980; Xiao, *et al.*, 2007). The model relies on the assumption of 'staged-budgeting': for example consumers are assumed to first decide on the proportion of their budget to spend on transport, and then to decide how to allocate their transport budget between different modes. While analytically convenient, this assumption is likely to be flawed.



emission coefficients, but the source of these is not made explicit. The results also contradict the econometric evidence on direct rebound effects, since carbon emissions for heating and transport are estimated to increase. Furthermore, Brännlund *et al.* use an iterative estimation procedure, but only present the results from the first estimation step. This weakness is overcome by Mizobuchi (2007), who follows a very similar approach to Brännlund *et al.*, but applied to Japanese households. Despite the differences in data sources and estimation procedures, the estimated rebound effects are broadly the same. However, Mizobuchi also examines the effect of the additional capital cost of energy efficient equipment and finds that these reduce the rebound effect significantly.

The third example adopts a different approach, using data on the marginal propensity to spend of different income groups in Sweden. Alfredsson (2004) calculates the direct and indirect energy consequences of 'greener' consumption patterns, which include both technical changes, such as buying a more fuel-efficient car, and behavioural changes such as car sharing. In the case of 'greener' food consumption (e.g. shifts towards a vegetarian diet), the total energy consumption associated with food items is reduced by around 5% and total expenditure on food items is reduced by 15%. But the re-spending of this money on a variety of items, notably travel and recreation, leads to indirect energy consumption that more than offsets the original energy savings (i.e. backfire). The results for a shift towards 'greener' travel patterns are less dramatic, but the

secondary effects from re-spending reduce the overall energy savings by almost one third. A comprehensive switch to green consumption patterns in travel, food and housing is estimated to have a rebound effect of 35%.

Secondary effects are relatively large in this example because 'green' consumption reduces expenditure on more than energy alone. Also, the results from such studies depend upon the methodology and assumptions used, as well as the types of household analysed and the particular shifts in consumption patterns that are explored. For example, a more recent study (Kanyama, *et al.*, 2006) using a similar model and approach to Alfredsson, but employing Swedish rather than Dutch data on energy intensity, finds that a shift to 'green' food consumption could reduce overall energy consumption. Closer examination reveals that this result follows largely from the assumption that greener diets are more expensive (owing to the higher cost of locally produced organic food), thereby leading to a negative 're-spending' effect.

In sum, the potential of embodied energy approaches to estimating secondary effects has yet to be fully explored. While the studies reviewed here suggest that secondary effects may sometimes be larger than commonly assumed, the conclusions may change once methodological weaknesses are addressed or a different choice of independent variable is made. Hence, at present the available evidence is too small to permit any general conclusions to be drawn.

4.5 Evidence for economy-wide effects from general equilibrium models

The economy-wide rebound effect represents the sum of the direct and indirect rebound effects and will depend upon the size, nature and location of the energy efficiency improvements. Given the number of confounding variables, it is likely to be very difficult to estimate through the econometric analysis of secondary data.

One approach, although it would not permit quantification of the overall effect, would be to identify those variables that should influence the size of direct and indirect effects and to estimate these empirically. Direct rebound effects for producers, for example, should be influenced by the own-price elasticity of demand for the relevant products, the share of energy in the total cost of production and the extent to which the cheaper energy services are able to substitute for capital, labour and materials (Saunders, 1992; Allan, *et al.*, 2006). Rebound effects may be expected to be larger in energy intensive sectors and also where the input mix is fairly flexible and where the demand for products is relatively price-elastic.

An alternative approach is to estimate the magnitude of economy-wide effects through energy-economic models of the macro-economy (Grepperud and Rasmussen, 2004). Despite the widespread use of such models within

energy studies (Bhattacharyya, 1996), it is only recently that attempts have been made to quantify economy-wide rebound effects in this way.³⁷ The literature is therefore extremely sparse, but now includes two insightful studies commissioned by the UK government (Allan, *et al.*, 2006; Barker and Foxon, 2006). A key distinction is between Computable General Equilibrium (CGE) models of the macroeconomy and those based upon econometrics. This section discusses some results from CGE models, while Section 4.5 discusses an application of a macro-econometric model to the rebound effect.

Computable General Equilibrium (CGE) models are widely used in the investigation of energy and climate policy, partly as a consequence of the ready availability of modelling frameworks and the associated benchmark data. This approach is informed by neoclassical economic theory, but can deal with circumstances that are too complex for analytical solutions.

CGE models are calibrated to reflect the structural and behavioural characteristics of particular economies and in principle can indicate the approximate order of magnitude of direct and indirect rebound effects from specific energy efficiency improvements. A CGE model should allow the impacts of such improvements to be isolated, since the counterfactual is simply a model run without any changes in energy efficiency, as well as allowing the rebound effect to be decomposed into its constituent components, such as

³⁷ A special edition of the Energy Policy journal published in 2000 provides a invaluable account of the state of the debate at that time, but does not include any modelling estimates of economy-wide rebound effects (Schipper, 2000)

substitution and output effects. In principle, CGE models also provide scope for sensitivity analysis, although in practice this appears to be rare.

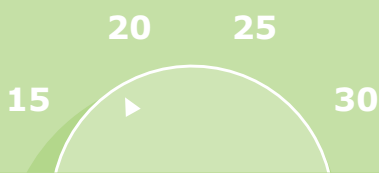
CGE models have a number of limitations (see Box 4.2) that have led many authors to question their realism and policy relevance (Barker, 2005). While developments in CGE methodology are beginning to overcome some of these weaknesses, most remain. Also, the predictive power of such models is rarely tested and different models appear to produce widely varying results for similar policy questions (Conrad, 1999). Hence, while CGE models may provide valuable insights, the quantitative results of such models should be interpreted with caution.

Eight CGE modelling studies of rebound effects have been identified and reviewed (Table 4.1). These models vary considerably in terms of the production functions used, the manner in which different inputs are combined (the 'nesting' structure), the assumed scope for substitution between different inputs, the treatment of labour supply, the manner in which government savings are recycled and other key parameters. These studies also vary widely in their simulation of energy efficiency improvements, with some introducing an across the board improvement and others introducing a specific improvement in an individual sector, or combination of sectors. This diversity, combined with the limited number of studies available again makes it difficult to draw any general conclusions.

The most notable result is that all of the studies find economy-wide rebound effects to be greater than 37% and most studies show either large rebounds

(>50%) or backfire. The latter was found in two studies of economies in which energy forms an important export and import commodity, suggesting that this is a potentially important and hitherto neglected variable. Allan *et al.* (2006) find a long-term rebound effect of 31% from across-the-board improvements in the energy efficiency of UK production sectors, including primary energy supply. This study is summarised in Box 4.3.

The results suggest that the magnitude of rebound effect depends upon a wide range of variables. While Saunders (1992) and others stress the importance of the 'elasticity of substitution' between energy and other inputs in production (Box 4.4), other characteristics such as the elasticity of supply of capital and labour, the own-price elasticity of demand for the product of each sector, the energy intensity of producing sectors, the scope for substitution between different consumption goods, the income elasticity of the demand for goods and the manner in which government revenue is redistributed are also potentially important. The contrasting results of Hanley *et al.* (2005) for the Scottish economy (rebound >100%) and Allan *et al.* (2006) for the UK economy (rebound ~ 37%) are revealing, since the assumed improvement in energy efficiency is the same in both cases (5% in all production sectors). The difference is primarily due to the relative sensitivity of export demand to changes in energy efficiency. While both studies assume that energy efficiency improvements are made in electricity generation, it is only in the Scottish case that this leads to a substantial increase in electricity exports – and hence in domestic energy consumption.



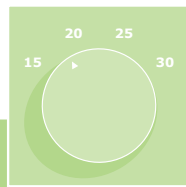
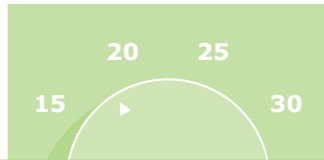
Box 4.2 Limitations of CGE models

- *Market and behavioural assumptions:* CGE models are based upon a number of standard neo-classical assumptions (e.g. utility maximization; perfect competition; constant returns to scale in production; etc.) that are poorly supported by empirical evidence. In particular, the possibility of 'win-win' policies, such as those aimed at encouraging energy efficiency, may be excluded if an economy is assumed to be at an optimal equilibrium.
- *Functional Forms:* The choice of utility and production functions is governed by the need for convenience and solvability, rather than realism and generally imposes restrictions on the behaviour of the economy being modelled. The choice of a different production function can lead models to predict different outcomes to an identical policy change. The most common approach is the 'nested constant elasticity of substitution' (CES) production function, but the manner in which this is implemented varies widely from one model to another. This structure also assumes that the optimum ratio of two inputs that are grouped together in a 'nest' is unaffected by either the level or price of other inputs ('separability'). However, this assumption is generally not supported by empirical evidence (Frondel and Schmidt, 2004).
- *Calibration and parameters:* CGE models are calibrated to benchmark data from a single year and adjustments are made to the data to ensure that the equilibrium assumption holds. The choice of base year for calibration is somewhat arbitrary and may influence the results. Some parameter values will be determined through this calibration, while others will be set externally on the basis of econometric literature. However, the time periods/regions/sectors on which this literature is based may not be appropriate to the model application, and the process of compiling parameter values may not always be transparent. Assumed parameter values could have a significant influence on the model results, but the calibration approach provides no information on the statistical reliability of individual estimates. Sensitivity tests are possible, but these are frequently confined to a small number of relevant parameters. Also, the modeling typically rests on the implicit assumption that such parameters will remain stable over time.
- *Sensitivity and transparency:* There exists considerable variation between CGE models so that care needs to be taken when comparing results. Changing some assumptions can sometimes generate very different simulated outcomes. The model results can be driven by assumptions that are not apparent to a reader not acquainted with the model. But CGE models are not necessarily a 'black box': transparency may be considerably improved by providing information on key features and assumptions and explaining model results with reference to economic theory.
- *Treatment of Technical Change:* In most CGE models, technological change is assumed to be costless and exogenous and thus not related to or determined from within the system. A common approach is to assume that energy efficiency improves at a constant rate over time, but this fails to capture price/policy induced innovation and other characteristics of endogenous technical change.
- *Time scales:* Many (but not all) CGE models simulate equilibrium states of the economy and do not consider the dynamics of adjustment and the associated costs. The solutions are assumed to refer to the 'long-run', but the time period that this represents may be unclear. For example, transport and building infrastructures take much longer to adjust than other types of capital equipment.

Table 4.1 Summary of CGE studies of rebound effects

Author/ Date	Country or region	Nesting structure	ESUB with energy	Assumed energy improvements	Estimated rebound effect	Comments
Semboja, 1994a	Kenya	Elec, fuel, K, L	1.0	Two scenarios: an improvement of energy production efficiency and an improvement in energy use efficiency.	>100%	Intuitive presentation, no sensitivity tests, lack of transparency.
Dufournaud <i>et al.</i> , 1994	Sudan	Utility functions	0.2 and 0.4.	100%, 150% and 200% improvement in efficiency of wood-burning stoves	47-77%.	Models efficiency improvements in domestic stoves. Wide range of sensitivity tests and good explanation of the factors at work.
Vikstrom, 2004	Sweden	(KE)L	Values range from 0.07 to 0.87.	15% increase in energy efficiency in non-energy sectors and 12% increase in energy sectors.	50-60%	Applies to 1957-1962 period in which known changes in energy efficiency productivity and structure are combined in turn. Results apply only to energy efficiency component
Washida, 2004	Japan	(KL)E	0.5.	1% in all sectors modelled as change in efficiency factor for use of energy in production	53% in central scenario	Presentation unclear, although there is some sensitivity analysis, including varying elasticity of substitution from 0.3 to 0.7 jointly with other parameters. Rebound effect increases as energy/value added, labour/capital and level of energy composite substitution elasticities increase.
Grepperud and Rasmussen 2004	Norway	(KE)L	Between 0 & 1	Doubling of growth rates of energy productivity. Four sectors have electricity efficiency doubled, & two have oil efficiency doubled.	Small for oil but >100% for electricity	Model is simulated dynamically with a counterfactual case in which projections of world economic growth, labour force growth, technological progress and net foreign debt are assumed until 2050.
Glomsrød and Taoyuan, 2005	China	Elec, fuel, K, L	1.0	Business-as-usual scenario compared to case where costless investments generate increased investments and productivity in coal cleaning - lowering price and increasing supply	>100%	Coal intensive sectors benefit, as does whole economy due to high use of coal in primary energy consumption. Also examines cases where coal use is subject to emissions tax.
Hanley <i>et al.</i> , 2005	Scotland	(KL)(EM)	0.3.	5% improvement in efficiency of energy use across all production sectors	>100%	Region is significant electricity exporter and result depends in part on increased electricity exports
Allan <i>et al.</i> , 2006	UK	(KL)(EM)	0.3	5% improvement in efficiency of energy use across all production sectors (including energy sectors).	37% in central scenario	See Box 4.3

Notes: The production functions combine inputs into pairs, or 'nests'. For example, a nested production function with capital (K), labour (L) and energy (E) inputs, could take one of three forms, namely: K(LE); (KE)L. ESUB means the elasticity of substitution between energy and other inputs. Interpretation depends upon the nesting structure. For example, for K(LE) ESUB refers to the elasticity of substitution between L and E, while for (KL)E it refers to elasticity of substitution between (KL) and E.



Box 4.3 CGE estimates of economy-wide rebound effects for the UK

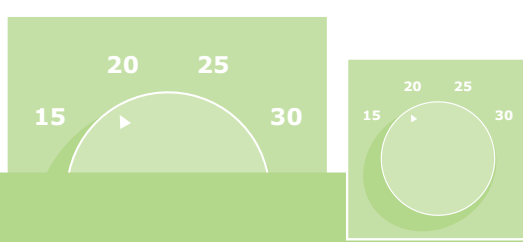
Allan *et al.* (2006) estimate economy-wide rebound effects for the UK following a 5% across-the-board improvement in the efficiency of energy use in all production sectors. Since their model allows for the gradual updating of capital stocks, they are able to estimate a short run rebound effect of 50% and a long-run effect of 31% (which contradicts most of the literature, which estimates long-run effects to be larger).

The energy efficiency improvements increase long-run GDP by 0.17% and employment by 0.21%. They have a proportionally greater impact on the competitiveness of energy intensive sectors which is passed through in lower product prices despite a 0.3% increase in real wages. Output is increased in all sectors, with the iron and steel and pulp and paper sectors benefiting the most with long-run increases of 0.67% and 0.46% respectively. In contrast, the output of the oil refining and electricity industries (i.e. oil and electricity demand) is reduced, with the price of conventional electricity falling by 24% in the long-run. This fall in energy prices contributes a significant proportion of the overall rebound effect and results from both cost reductions in energy production - due to the energy efficiency improvements - and reduced energy demand.

Allan *et al.* are using an economic rather than thermodynamic measure of energy efficiency, but a 5% improvement may nevertheless be impractical for industries such as electricity generation and oil refining which are operating close to thermodynamic limits. It would also require major new investment and take time to be achieved. The results suggest that the economy-wide rebound effect would be smaller if energy efficiency improvements were confined to energy users, but this scenario was not investigated. Moreover, the results suggest that energy efficiency improvements in the energy supply industry may be associated with large rebound effects.

A notable feature of this study is the use of sensitivity tests. Varying the assumed elasticity of substitution between energy and non-energy inputs between 0.1 and 0.7 (compared to a baseline value of 0.3) had only a small impact on economic output (from 0.16% in the low elasticity case to 0.10% in the high case), but a major impact on the rebound effect. This varied from 7% in the low case to 60% in the high case. Grepperud and Rasmussen (2004) report similar results, which highlights the importance of this parameter for CGE simulations. Unfortunately, as shown in Box 4.4, the empirical basis for this parameter is weak.

Varying the elasticity of demand for exports was found to have only a small impact on GDP and energy demand, suggesting that the energy efficiency improvements had only a small impact on the international competitiveness of the relevant industries. However, different treatments of the additional tax revenue were found to be important, with recycling through lower taxes increasing the rebound effect from 31% to 40%.



Box 4.4 Parameterising CGE models

A key parameter in CGE models is the so-called elasticity of substitution between different inputs. This determines the extent to which one input can substitute for another while keeping output constant. The elasticity of substitution between energy and other inputs has a strong influence on the estimated magnitude of rebound effects (Grepperud and Rasmussen, 2004).

There are a large number of empirical estimates of elasticities of substitution between different inputs, within different countries and sectors and over different periods of time. In principle, this literature could be used as a basis for selecting appropriate parameter values in individual CGE models. In practice, however, there is only a tenuous relationship between the parameters estimated by empirical studies and those assumed by the models. In particular, CGE models:

- use different types of production function from those estimated within empirical studies;
- use different definitions of the elasticity of substitution from those estimated with empirical studies;
- combine inputs into nests while most empirical studies do not;
- assume that the scope for substitution within a nest is independent of the level or prices of other inputs, while most empirical studies do not;
- make assumptions about the elasticity of substitution between different nests, while most empirical studies provide estimates of the elasticity of substitution between individual pairs of inputs.

In addition: the process of compiling parameter values is rarely transparent; sensitivity tests are uncommon; the empirical studies frequently apply to different sectors, time periods and levels of aggregation to those represented by the model; and different models use widely different assumptions. These observations suggest that the empirical basis for most CGE models is relatively weak.

All but one of the models explore the implications of energy efficiency improvements in production sectors and the CGE literature offers relatively little insight into the implications of energy efficiency improvements in consumer goods. Since there are differences across income groups, this would require a much greater detail on the demand side of the CGE models than is commonly the case, together with more accurate representations of household behaviour.

CGE models also simulate energy efficiency improvements as pure 'energy augmenting technical change', which is assumed to be costless. Of the studies reviewed here, only Allan *et al.* (2006) consider the implications of additional costs associated with energy efficiency improvements and they find that rebound effects are correspondingly reduced.

In summary, given the small number of studies available, the diversity of approaches and the methodological

weaknesses of the CGE approach, it is not possible to draw any general conclusions regarding the size of economy-wide rebound effect. Indeed, since the most important insight from this literature is that the economy-wide rebound effect varies widely from one circumstance to another, a general statement on the size of such effects may be misleading. Perhaps the most useful application of this approach would be to investigate the determinants of rebound effects more systematically. It is worth noting, however, that the available studies suggest that economy-wide effects are frequently large and that the potential for backfire cannot be ruled out. Moreover, these effects derive from 'pure' energy efficiency improvements and therefore do not rely upon simultaneous improvements in the productivity of capital and labour inputs.

4.6 Evidence for economy-wide effects from macro-econometric models

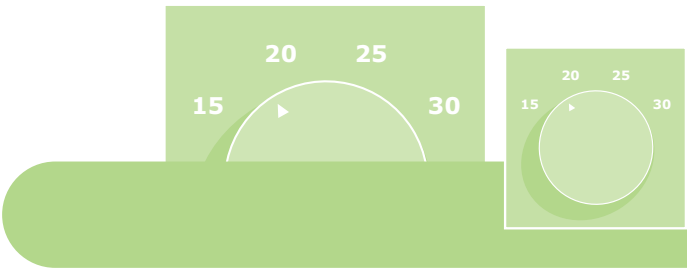
Macro-econometric models can overcome several of the weaknesses of CGE modelling while at the same time providing a greater level of disaggregation that permits the investigation of specific government policies. Their usefulness can be further enhanced if they can be effectively linked to 'bottom-up models'³⁸

of particular sectors, such as electricity generation, where representation of specific technologies is desirable. In contrast to their CGE counterparts, macro-econometric models do not rely upon restrictive assumptions such as constant returns to scale and perfect competition. They also replace the somewhat ad-hoc use of parameter estimates with econometric equations estimated for individual sectors which implicitly reflect non-optimising behaviour, such as the apparent neglect of cost-effective opportunities to improve energy efficiency. However, this greater realism is achieved at the expense of greater complexity, more onerous data requirements and higher costs in developing and maintaining such models. This section describes the use of one such model (MDM-E3)³⁹ to explore economy-wide rebound effects in the UK (Barker and Foxon, 2006; Barker, *et al.*, 2007). At present, this appears to be the only application of such models to the economy-wide rebound effect.

MDM-E3 combines time-series econometric relationships and cross-sectional input-output relationships with detailed modelling of the energy sector (Junankar, *et al.*, 2007). It distinguishes 27 investment sectors, 51 categories of household expenditure and 41 industries/commodities. The model includes equations for consumption, investment, employment and trade for each of the 41 industries, together with equations for wage rates, output and

³⁸ 'Bottom-up' or engineering-economic models usually focus upon individual sectors and energy services and contain detailed information on the performance and cost of energy-using equipment. They simulate the ageing and replacement of this equipment and seek to minimise the net cost of energy services given appropriate assumptions about individual and organisational investment behaviour.

³⁹ The Cambridge Multisectoral Dynamic Model of the UK energy-environment-economy (MDM-E3) is developed and maintained by Cambridge Econometrics Ltd and also used by the Cambridge Centre for Climate Change Mitigation Research (4CMR) at the Department of Land Economy, University of Cambridge.



commodity prices. The projected activity levels are used as inputs to an energy sub-model, along with data on temperature and energy prices and assumptions about technical change. This leads to estimates of total energy demand, fuel and electricity use by 13 categories of user and electricity prices. The sub-model then feeds this information back into the main model by adjusting the input-output coefficients for producers and consumer expenditures on energy.⁴⁰ The two models are run iteratively to reach a stable solution over the projection period. Both the main model and electricity sub-model use modern 'cointegration' techniques to distinguish short-term dynamic responses from long-term relationships (Engle and Granger, 1987; Cambridge Econometrics, 2005)

In a study conducted on behalf of the UK government, MDM-E3 was used to simulate the macroeconomic impact of a number of UK energy efficiency policies over the period 2000 to 2010 (Barker and Foxon, 2006). The first stage was to develop exogenous estimates of the 'gross' energy savings from each of these policies, the 'net' energy savings which allow for the estimated direct rebound effects associated with each policy and the associated investment costs. While Barker and Foxon (2006) state that the direct rebound effect from energy efficiency improvements by producers was assumed to be zero, the output effects from such improvements are subsequently modelled. Hence, it is the substitution effect from such improvements that is assumed to be zero.

The next stage was to run the model for a base case that included the full set of

energy efficiency policies, together with reference scenario that did not. The estimated net energy savings were included directly in the energy demand equations for each sector, the results of which were then fed back into the macroeconomic model. Given the projected lower energy demand, lower energy prices and hence lower energy costs for each sector, the model projected a range of secondary effects including increased output and changes in trade patterns. The estimated investment costs of the energy efficiency measures were also taken into account by including them in the relevant investment equations. Overall, the cost-effective energy efficiency measures contributed to a 1.26% increase in GDP by 2010 (relative to the reference scenario) a 0.84% increase in employment and a slight increase in imports. Energy consumption was 13.8% lower than in the reference scenario, even after allowing for economy-wide rebound effects.

Indirect rebound effects were estimated as the difference between the energy savings projected by the model and the estimated net energy savings, expressed as a percentage of the estimated gross energy savings. The base run led to an estimated indirect rebound effect of 11% by 2010. Closer inspection shows that indirect rebound effects were higher in the energy intensive industries (25%) and lower for households and transport (7%) (the opposite to what was assumed for direct effects). The primary source of the indirect effects was substitution between energy and other goods by households, together with increases in output by (particularly energy intensive) industry, which in turn

⁴⁰ This contrasts with other model frameworks, in which projections from a macroeconomic model are simply used as inputs into an energy sub-model, without any feedback from the latter.

led to increased demand for both energy and energy-intensive intermediate goods. Increases in consumers' real income contributed relatively small rebound effects (0.2%).

The direct rebound effects were estimated to reduce overall energy savings by 15%, leading to an estimated economy-wide rebound effect of 26% in 2010. Indirect effects appeared relatively insensitive to variations in energy and carbon prices. The authors claim that the results support Grubb's (1990) argument that policy-induced energy efficiency improvements are associated with small rebound effects because they focus on energy services with a low own-price elasticity as a consequence of various market failures. This is misleading, however: first, because this argument applies to direct rebound effects rather than the indirect effects being modelled; and second because these services should become more price elastic if the market failures are overcome.

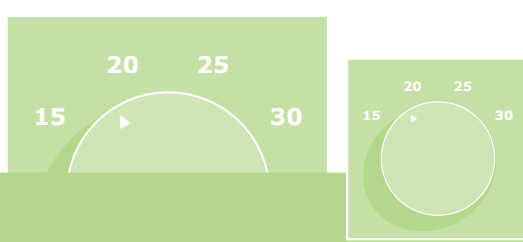
The macro-econometric approach exemplified by MDM-E3 appears to offer a more robust approach to estimating economy-wide rebound effects than CGE modelling. Nevertheless, there are a number of reasons why this particular study may underestimate economy-wide rebound effects. First, while output effects are estimated, the substitution between (cheaper) energy services and other inputs within production sectors is ignored. Also, the direct rebound effects for consumers have to be estimated rather than modelled. Second, the modelling implicitly assumes 'pure' energy efficiency improvements, with no associated improvements in the productivity of other inputs. But if energy efficient technologies are commonly associated with such improvements,

rebound effects could be larger. Third, the model does not reflect the indirect energy consumption embodied within the energy efficient technologies themselves. While the extra investment is taken into account, it appears to reduce the overall energy consumption associated with investment rather than increase it. Finally, the model confines attention to national energy use and ignores the indirect energy consumption associated with increased imports and tourism. This omission could be significant from a climate change perspective, since it corresponds to ~40% of the extra domestic output.

In sum, while greater confidence can be placed in this estimate of economy-wide rebound effects than those from CGE models, there are a number of reasons why this study may underestimate the full effect. Also, any similarity between this result and that of Allan *et al.* (2006) is spurious, since they use different approaches to model different types of rebound effect from different types and size of energy efficiency improvement in different sectors.

4.7 Summary

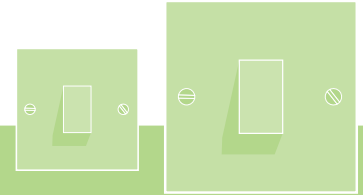
- There are very few quantitative estimates of indirect and economy-wide rebound effects and those that are available have a number of flaws. While a number of methodological approaches are available to estimate these effects, the limited number of studies to date provides an insufficient basis to draw any general conclusions.
- Techniques are available to estimate the embodied energy associated with energy efficiency improvements, but



the potential of these techniques has yet to be fully exploited. Most studies focus on domestic buildings and demonstrate that embodied energy associated with energy efficient buildings varies widely between different building types, designs and contexts. In most cases, the embodied energy is more than outweighed by the direct energy savings during the building life-cycle, but the contribution of embodied energy to the economy-wide rebound effect is generally ignored.

- The secondary effects associated with energy efficiency improvements by households may be estimated through a combination of embodied energy analysis and econometric models of consumer behaviour. Only a handful of studies have adopted this approach, and these give estimates of between 33% and 170% for direct and secondary effects combined. However, these studies have a number of weaknesses, and the results are very dependent upon the particular application as well as the data and methodologies employed.
- CGE studies suggest that the magnitude of economy-wide rebound effects depend very much upon the sector where the energy efficiency improvements take place and are sensitive to a number of variables. While only a handful of studies are available, they suggest that economy-wide rebound effects may frequently exceed 50% and the potential for backfire cannot be ruled out. Moreover, these rebound effects derive from 'pure' energy efficiency improvements and therefore do not rely upon simultaneous improvements in the productivity of capital and labour.
- The results of CGE studies results apply solely to energy efficiency improvements by producers, so therefore cannot be extended to energy efficiency improvements by consumers. Also, the small number of studies available, the diversity of approaches used and the methodological weaknesses of CGE modeling all suggest the need for caution when interpreting these results.
- In principle, more robust estimates of the economy-wide rebound effect may be obtained from macro-econometric models of national economies. Barker and Foxon (2006) use this approach to estimate an economy-wide rebound effect of 26% from current UK energy efficiency policies. However, there are a number of reasons why this study may have underestimated the economy-wide rebound effect.
- The main insight from this evidence base is the dependence of the economy-wide rebound effects on the nature and location of the energy efficiency improvement, which makes any general statements regarding the magnitude of such effects questionable. However, while little confidence can be placed in the quantitative estimates, the frequent finding that economy-wide rebound effects exceed 50% should give cause for concern. Extending and improving this evidence base should therefore be a priority for future research.

5. The evidence for ‘backfire’



This section summarises the empirical evidence for the Khazzoom-Brookes postulate, focusing in particular on the work of W.S. Jevons, Len Brookes and Harry Saunders. An in-depth examination of this evidence is contained in *Technical Report 5*.

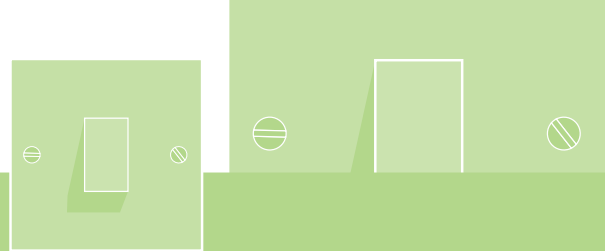
The ‘Khazzoom-Brookes’ (K-B) postulate claims that economy-wide rebound effects exceed unity, so that energy efficiency improvements lead to backfire. The term was first coined by Saunders (1992) who refers specifically to the energy efficiency improvements that result from technical change, rather than from the substitution of other inputs for energy (Box 2.1). Also, Saunders’s statement of the K-B postulate implies that ‘pure’ energy efficiency improvements will increase energy consumption, regardless of any associated improvements in the productivity of capital, labour and materials. However, this distinction is not

made by other advocates of the K-B postulate, including Len Brookes himself (Brookes, 2000).

Neither Brookes nor Saunders cite empirical estimates of direct, indirect and economy-wide rebound effects, but instead develop their case through a mix of theoretical argument, mathematical modelling, anecdotal examples and ‘suggestive’ evidence from econometric analysis and economic history (Box 5.1). It is these ‘indirect’ sources of evidence that are reviewed in this section. None of this research provides quantitative estimates for the size of the economy-wide rebound effect and the majority of the studies make no reference to the rebound effect at all. Instead, they provide evidence that may arguably be used in support of the K-B postulate, either on theoretical grounds or on the basis of historical experience. Like the K-B postulate itself, this evidence frequently

Box 5.1 Sources of evidence considered indirectly relevant to the K-B postulate

- The relationship between macro-level energy productivity and micro-level thermodynamic efficiency (Berndt, 1978; 1990; Ang, 2006).
- The relationship between energy productivity and total factor productivity (Schurr, 1982; 1983; 1985; Jorgenson, 1996).
- The contribution of energy to economic growth (Toman and Jemelkova, 2003; Stern and Cleveland, 2004).
- The implications of energy augmenting technical change within neoclassical production and growth theory (Saunders, 1992; 2007).
- Decomposition analysis of historical trends in energy consumption (Schipper and Grubb, 2000).
- Econometric studies of the ‘causal’ relationships between energy consumption and economic growth (Kraft and Kraft, 1978; Stern, 1993).
- Empirically validated alternatives to conventional models of economic growth that include energy or useful work as a factor of production (Kummel, *et al.*, 2002; Ayres and Warr, 2005).



runs counter to conventional wisdom. However, in all cases it is suggestive rather than definitive.

This section is structured as follows:

Section 5.1 provides a historical context to the debate, including Jevons' 19th century example of the effect of energy efficiency improvements in steam engines, together with more contemporary examples of comparable 'general-purpose' technologies. This introduces the central theme of this section: namely that the evidence used in support of the K-B postulate is closely linked to a broader question regarding the contribution of energy to economic growth.

Section 5.2 summarises Brookes' arguments in favour of the postulate, identifies some empirical and theoretical weaknesses and examines whether more recent research supports Brookes' claims. Section 5.3 provides a non-technical summary of Saunders' work, highlighting the dependence of these results on specific theoretical assumptions and the questions it raises for standard economic approaches.

Section 5.4 investigates the empirical evidence regarding the scope for substitution between energy and capital. It shows how 30 years of research have failed to reach a consensus on this issue and argues that the relationship between this and the rebound effect is more complex than some authors have suggested. Section 5.5 examines further evidence on the contribution of energy to economic growth and points to the interesting parallels between Brookes'

arguments and those of contemporary ecological economists. While the evidence remains ambiguous and open to interpretation, the central argument is that energy – and by implication energy efficiency – plays a significantly more important role in economic growth than is assumed within mainstream economics. Section 5.6 highlights some of the implications of this finding for the economy-wide rebound effect. Section 5.7 concludes.

5.1 Historical perspectives

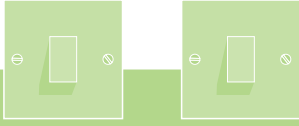
The argument that improved energy efficiency will increase economy-wide energy consumption was first made by W.S. Jevons in 1865, who used the example of the steam engine:

"... it wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.....Every improvement of the engine when effected will only accelerate anew the consumption of coal..." (Jevons, 1865)

Jevons cites the example of the Scottish iron industry, in which:

"..... the reduction of the consumption of coal, per ton of iron, to less than one third of its former amount, has been followed....by a tenfold increase in total consumption, not to speak of the indirect effect of cheap iron in accelerating other coal consuming branches of industry..." (Jevons, 1865)

According to Jevons, the early Savory engine for pumping floodwater out of coal



mines "...consumed no coal because its rate of consumption was too high." It was only with the subsequent improvements by Watt and others that steam engines became widespread in coal mines, facilitating greater production of lower cost coal which in turn was used by comparable steam engines in a host of applications. One important application was to pump air into blast furnaces, thereby increasing the blast temperatures, reducing the quantity of coal needed to make iron and reducing the cost of iron (Ayres, 2002). Lower cost iron, in turn, reduced the cost of steam engines, creating a positive feedback cycle. It also contributed to the development of railways, which lowered the cost of transporting coal and iron, thereby increasing demand for both.

Jevons highlighted the fact that improvements in the thermodynamic efficiency of steam engines were intertwined with broader technical change, including: "... contrivances, such as the crank, the governor, and the minor mechanism of an engine, necessary for regulating, transmitting, or modifying its power..." (Jevons, 1865).⁴¹ These developments were essential to the increased use of steam engines as a source of motive power and demonstrate how improvements in thermodynamic efficiency are frequently linked to broader improvements in technology and total factor productivity.

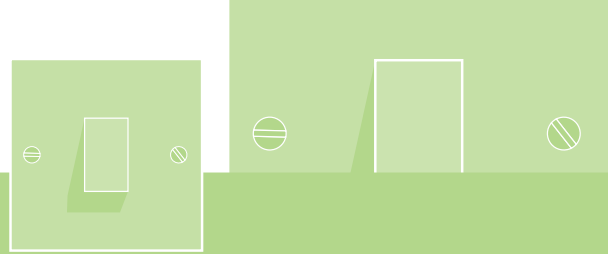
More recently, Rosenberg (1989) has cited the comparable example of the Bessemer process for steelmaking:

"[the Bessemer process] was one of the most fuel saving innovations in the history of metallurgy [but] made it possible to employ steel in a wide variety of uses that were not feasible before Bessemer, bringing with it large increases in demand. As a result, although the process sharply reduced fuel requirements per unit of output, its ultimate effect was to increase...the demand for fuel." (Rosenberg, 1989)

The low cost Bessemer steel initially found a large market in the production of steel rails, thereby facilitating the growth of the rail industry, and later in a much wider range of applications including automobiles. However, the mild steel produced by the Bessemer process is a very different product to wrought iron (which has a high carbon content) and is suitable for a much wider range of applications. Hence, once again, the improvements in the thermodynamic efficiency of production processes are deeply entwined with broader developments in process and product technology.

These examples relate to energy efficiency improvements in the early stages of development of energy intensive process technologies and intermediate goods that have the potential for widespread use in multiple applications. It

41 Another factor was the development of high pressure boilers after 1840 (Hills, 1989). Compared to the early Newcomen engine, the Watt engine used only 2/5 of the amount of coal per unit of output, while compared to the early Watt engine, high pressure steam turbines in the earlier 20th-century used only one sixth (Crafys, 2003). According to Atack (1979), the annual cost of a horsepower of steam fell by just over 80% between the 1820s and the 1890s.



is possible that the same consequences may not follow for energy efficiency improvements in mature and/or non-energy intensive process technologies and intermediate goods that have a relatively narrow range of applications. Similarly, the same consequences may not follow from improvements in consumer technologies that supply energy services with a low own-price elasticity and where energy represents only a small share of total costs. (Ayres, 2002). The relevance and importance of these distinctions is discussed further below.

A historical perspective on rebound effects is provided by Fouquet and Pearson (2006), who present some remarkable data on the price and consumption of lighting services in the UK over a period of seven centuries (Table 5.1). Per capita consumption of lighting services grew much faster than per capita GDP throughout this period, owing in part to continuing reductions in the price of lighting services (£/lumen hour). This, in turn, derived from continuing improvements in the thermodynamic efficiency of lighting technology, in combination with continuing reductions in the real price of lighting fuel (itself, partly a consequence of improvements in the thermodynamic efficiency of energy supply). In this case, improvements in lighting technology were substantially more important than improvements in energy supply (in the ratio of 180 to 1 over the period 1800 to 2000).

Per capita lighting consumption increased by a factor of 6566 between 1800 and 2000, largely as a consequence of the falling cost of lighting services relative to income, but also as a result of the boost

to per capita GDP provided by the technical improvements in lighting technology. Since lighting efficiency improved by a factor of 1000, the data suggest that per capita energy consumption for lighting increased by a factor of six. In principle, the direct rebound effect could be estimated by constructing a counterfactual scenario in which lighting efficiencies remained at 1800 levels. But this would be a meaningless exercise over such a time interval, given the co-evolution and interdependence of the relevant variables and the interrelationship between energy consumption and economic growth (Box 5.2). To the extent that the demand for lighting is approaching saturation in many OECD countries, future improvements in lighting efficiency may be associated with smaller rebound effects. Nevertheless, this historical perspective gives cause for concern over the potential of technologies such as compact fluorescents to reduce energy consumption in developing countries.

5.2 Energy productivity and economic growth

Despite their far-reaching implications, Jevons' ideas were neglected until comparatively recently and contemporary advocates of energy efficiency are frequently unaware of them. While a 1980 paper by Daniel Khazzoom stimulated much research and debate on the direct rebound effect (Besen and Johnson, 1982; Einhorn, 1982; Henly, *et al.*, 1988; Lovins, *et al.*, 1988), most researchers ignored the long-term, macroeconomic

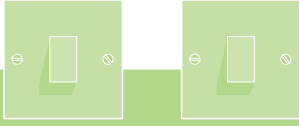


Table 5.1 Seven centuries of lighting in the UK

Year	Price of lighting fuel	Lighting efficiency	Price of lighting services	Consumption of light per capita	Total consumption of light	Real GDP per capita
1300	1.50	0.50	3.0	-	-	0.25
1700	1.50	0.75	2.0	0.17	0.1	0.75
1750	1.65	0.79	2.1	0.22	0.15	0.83
1800	1.0	1	1	1	1	1
1850	0.40	4.4	0.27	3.9	7	1.17
1900	0.26	14.5	0.042	84.7	220	2.9
1950	0.40	340	0.002	1528	5000	3.92
2000	0.18	1000	0.0003	6566	25630	15

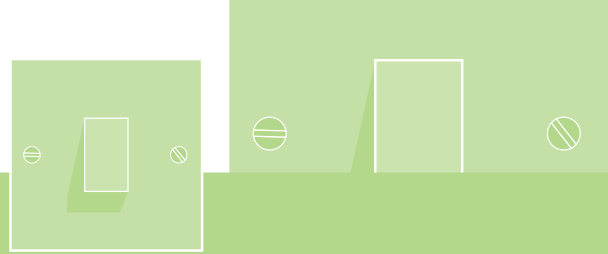
Note: 1800=1.0 for all indices Source: Fouquet and Pearson (2006)

Box 5.2 Energy consumption and economic growth - neoclassical and ecological perspectives

Numerous studies have demonstrated strong correlations between economic output and energy consumption at different levels of aggregation and over different periods of time. But this leaves open the question of to what extent the growth in economic output can be considered a cause of the increased energy consumption, and to what extent the growth in energy inputs can be considered a cause of the increased economic output. Alternatively there could be a synergistic relationship between the two, with each causing the other as part of a positive feedback mechanism (Ayres and Warr, 2002).

The conventional wisdom (as represented by both neoclassical and 'endogenous' growth theory) is that increases in energy inputs play a relatively minor role in economic growth, largely because energy accounts for a relatively small share of total costs (Jones, 1975; Denison, 1985; Gullickson and Harper, 1987; Barro and Sala-I-Martin, 1995). Economic growth is assumed to result instead from the combination of increased capital and labour inputs, changes in the quality of those inputs and increases in total factor productivity that are frequently referred to as technical change. However, this view has been contested by ecological economists, who argue that the increased availability of high quality energy inputs has been the primary driver of economic growth over the last two centuries (Cleveland, *et al.*, 1984; Beaudreau, 1998; Kummel, *et al.*, 2000). According to this view, the productivity of energy inputs is substantially greater than is suggested by its small share of total costs.

The conventional and ecological perspectives reflect differing assumptions and are supported by conflicting empirical evidence. A difficulty with both is that they confine attention to the relationship between *energy* consumption and economic growth. But the reason that energy is economically significant is that it is used to perform useful work - either in the form of mechanical work (including electricity generation) or in the production of heat (Ayres and Warr, 2005). More useful work can be obtained with the same, or less, energy consumption through improved energy efficiency. Hence, if increases in energy inputs contribute disproportionately to economic growth, then improvements in energy efficiency may do the same. Conversely, if increases in energy inputs contribute little to economic growth, then neither should improvements in energy efficiency. This suggests that differing views over the size of the economy-wide rebound effect may partly reflect differing views over the relationship between energy and economic growth.



implications that were Jevons' primary concern. However, Jevons' arguments have been taken up with some vigour by the British economist, Len Brookes, who has developed coherent arguments in favour of the K-B postulate and combined these with critiques of government energy efficiency policy (Brookes, 1978; 1984; 1990; 2000; 2004). Brookes work has prompted a fierce response from critics (Grubb, 1990; Herring and Elliot, 1990; Toke, 1990; Grubb, 1992), to which Brookes has provided a number of robust responses (Brookes, 1992; 1993).⁴²

Brookes (2000) argues that "...The claims of what might be called the Jevons school are susceptible only to suggestive empirical support", since estimating the macroeconomic consequences of individual improvements in energy efficiency is practically impossible. He therefore relies largely on theoretical arguments, supported by indirect sources of evidence, such as historical correlations between various measures of energy efficiency, total factor productivity, economic output and energy consumption (Schurr, 1984; 1985). A key argument runs as follows:

"...it has been claimed since the time of Jevons (1865) that the market for a more productive fuel is greater than for less productive fuel, or alternatively that for a resource to find itself in a world of more efficient use is for it to enjoy a reduction in its implicit price with the obvious implications for demand."

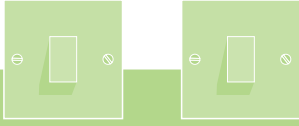
However, Brookes' use of the term

'implicit price' is confusing. Individual energy efficiency improvements do not change the price of input energy, but instead lower the effective price of output energy, or useful work. For example, motor-fuel prices may be unchanged following an improvement in vehicle fuel efficiency, but the price per vehicle kilometre is reduced. The 'obvious implications' therefore relate to the demand for useful work, and not to the demand for energy commodities themselves. While the former may be expected to increase, energy demand may either increase or decrease depending upon the price elasticity of demand for useful work and the associated indirect rebound effects.

Of course, the combined impact of multiple energy efficiency improvements could lower energy demand sufficiently to reduce energy prices and thereby stimulate a corresponding increase in economy-wide energy demand. This forms one component of the economy-wide rebound effect. But while it is obvious that the overall reduction in energy consumption will be less than microeconomic analysis suggests, this theoretical argument appear to be an insufficient basis for claiming that backfire is inevitable.

Brookes also criticises the assumption that energy service demand will remain fixed while the marginal cost of energy services falls under the influence of raised energy efficiency, and the related assumption that individual energy savings can be added together to produce an

42 One of these critics, Horace Herring, is now more sympathetic to the K-B postulate (Herring, 2006)



estimate of what can be saved over the economy as a whole. In both cases, Brookes is highlighting the persistent neglect of both direct and indirect rebound effects in the conventional assessment of energy efficiency opportunities. However, arguing that the economy-wide rebound effect is greater than zero is different from arguing that it is greater than one – as the K-B postulate suggests.

Brookes marshals a number of other arguments in support of the K-B postulate that appear more amenable to empirical test. In doing so, he highlights some important issues regarding the relationship between energy consumption and economic growth. The three most important arguments may be characterised as follows:

- *The productivity argument:* The increased use of higher quality forms of energy (especially electricity) has encouraged technical change, substantially improved total factor productivity and driven economic growth. Despite the substitution of energy for other inputs, this technical change has stimulated a sufficiently rapid growth in economic output that aggregate energy efficiency has **improved** at the same time as aggregate energy consumption has **increased**.⁴³ This pattern may be expected to continue in the future.

The productivity argument rests upon two separate, but related sources of empirical evidence. First, the work of Sam Schurr and colleagues on the historical importance of changes in energy quality (notably electrification) in driving productivity growth (Schurr, *et al.*, 1960; Schurr, 1984; 1985). Second, the work of Jorgenson and others on the direction of technical change (Jorgenson, 1984; Hogan and Jorgenson, 1991). Contrary to standard assumptions, Jorgenson's results suggest that, at the level of individual sectors, the contribution of technical change has been to increase energy intensity over time, rather than reduce it.⁴⁴ This work is also cited as suggestive evidence for the K-B postulate by Saunders (1992).

- *The endogeneity argument:* A common approach to quantifying the 'energy savings' from energy efficiency improvements is to hold energy intensity fixed at some historic value and estimate what consumption 'would have been' in the absence of those improvements (Geller, *et al.*, 2006). The energy savings from energy efficiency improvements are then taken to be the difference between the actual demand and the counterfactual scenario. But if the energy efficiency improvements are a **necessary condition** for the growth in economic output, the construction

⁴³Between 1918 and 1973, the US economy experienced substantial increases in both total factor productivity and energy efficiency, while energy prices fell in real terms. Even though energy use increased relative to labour and capital, the increased use of more flexible forms of energy (oil and electricity) enhanced the productivity of capital and labour sufficiently that energy use per unit of output fell (Schurr, 1982).

⁴⁴In their original study, Jorgenson and Fraumeni (1981) estimated the rate of change in the share of energy costs in the value of output of US manufacturing sectors, holding input prices constant. Contrary to conventional wisdom, Jorgenson and Fraumeni found 'energy-using' technical change in 29 out of 35 sectors. Generally, we would expect energy saving (using) technical change to be associated with falling (increasing) energy intensity. However, this may not always be the case, since it also depends upon the rate of change in total factor productivity (Sanstad, *et al.*, 2006). With energy-using technical change a decrease (increase) in the price of energy will raise (lower) total factor productivity.

of a counterfactual in this way is misconceived.⁴⁵ The endogeneity argument is not developed in detail by Brookes, but raises questions over the use of 'decomposition analysis'⁴⁶ to explore the rebound effect (Schipper and Grubb, 2000).

- *The accommodation argument:* Energy efficiency improvements are claimed to 'accommodate' an energy price shock so that the energy supply/demand balance is struck at a higher level than if energy efficiency had remained unchanged (Brookes, 1984). While not immediately obvious, this argument rests on the assumption that the income elasticity of 'useful' energy demand falls steadily as an economy develops, but is always greater than unity (Brookes, 1972). 'Useful' energy consumption is a quality-adjusted measure of aggregate energy consumption in which different energy types are weighted by their relative economic productivities (Adams and Miovic, 1968).

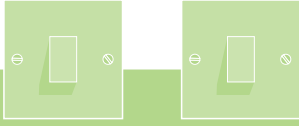
Technical Report 5 describes the historical research that forms the basis for these arguments, summarises how Brookes uses this research to support his case, identifies potential empirical and theoretical weaknesses and examines in detail whether more recent research confirms or contradicts Brookes' claims. It points to a number of flaws, both in the evidence itself and in the manner in which

Brookes uses this evidence to support his case. Specific criticisms include the following:

- Schurr's work applies primarily to the causal effect of shifts to higher quality fuels (notably electricity), rather than improvements in thermodynamic conversion efficiency or other factors that affect aggregate measures of energy efficiency. The effect of the latter on total factor productivity may not be the same as the effect of the former. Also, the patterns Schurr uncovered may not be as 'normal' as Brookes suggests and the link between energy efficiency improvements and improvements in total factor productivity appears to vary greatly, both over time and between different sectors and energy services.
- Neither Jorgenson's work itself, nor those of comparable studies consistently find technical change to be 'energy-using'. Instead, the empirical results vary widely between different sectors, countries and time periods and are sensitive to minor changes in econometric specification (Norsworthy, *et al.*, 1979; Roy, *et al.*, 1999; Welsch and Ochsens, 2005; Sanstad, *et al.*, 2006). Jorgenson's results rest on the erroneous assumption that the rate and direction of technical change is fixed, and more sophisticated models suggest that the magnitude and sign of technical

45 Technically, economic output and energy efficiency should be considered endogenous variables, since each influences the other. Conventional methodological approaches to estimating historical 'energy-savings', such as decomposition analysis, fail to do this.

46 Decomposition analysis expresses trends in aggregate quantities as the product of a number of different variables. For example, economy-wide energy consumption may be expressed into the product of population, GDP per capita and energy use per unit of GDP. An additive decomposition expresses the change in energy use over a particular period as the sum of the change in each of the right-hand side variables, while a multiplicative decomposition expresses the ratio of energy use at the end of the period to that at the beginning of the period as the product of comparable ratios for each of the right-hand side variables. Similar expressions can be developed at varying levels of detail for energy use within individual sectors. Thanks in part to the work of Lee Schipper and colleagues, decomposition analysis has become a widely used tool within energy economics (Ang, 1999).



change varies between sectors and types of capital as well as over time (Sue Wing and Eckaus, 2006). Also, the failure to check for the presence of 'cointegration'⁴⁷ in the data or to account for changes in energy quality means that some of the estimates could be either biased or spurious (Kaufmann, 2004). Moreover, even if energy-using technical change were to be consistently found, the relationship between this finding and the K-B postulate remains unclear.⁴⁸

- The endogeneity argument is rhetorically persuasive but lacks a firm empirical basis. The relative importance of energy efficiency improvements (however defined) compared to other forms of technical change in encouraging economic growth remains to be established.
- The 'accommodation' argument is based upon a highly simplified theoretical model of the world economy (Brookes, 1984), which is both unconventional in approach and difficult to interpret and calibrate. The model rests on the assumption that the income elasticity of 'useful' energy demand is always greater than unity, thereby allowing economic output to be represented as a linear function of useful energy inputs. An earlier study

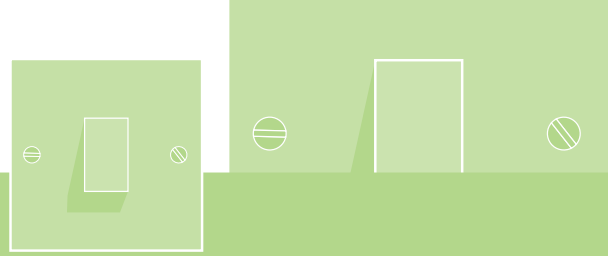
by Brookes (1972) provides some support for this hypothesis, but this has not been updated. Contemporary research on 'Environmental Kuznets Curves' has generally not tested this hypothesis, since it aggregates energy consumption on the basis of thermal content (Stern, 2004c; Richmond and Kaufmann, 2006b; 2006a). However, analysis by Dargay (1992) suggests that the income elasticity of useful energy demand has declined from above unity in the 1960s to around 0.7 in 1990, which contradicts Brookes' claims.

In sum, not only does each of the sources of evidence have empirical and theoretical weaknesses, but the extent to which they (individually and collectively) support the K-B postulate is open to question. Hence, while Brookes has highlighted some important issues and pointed to sources of evidence that challenge conventional wisdom, he has not provided a convincing case in support of the K-B postulate.

Perhaps the most important insight from Brookes' work is that improvements in energy productivity are frequently associated with improvements in the productivity of capital, labour and materials. In particular, historical experience suggests that improvements in

47 The presence of cointegration between two or more variables implies that one variable cannot move 'too far' away from another, because there is a long-term relationship between them. This may be because one variable 'causes' the other, or that they are both driven by a third, possibly omitted, variable. Cointegration analysis seeks to identify this relationship by detecting whether the irregular trends in a group of variables are shared by the group, so that the total number of unique trends is less than the number of variables. Failing to allow for cointegration can allow the precision of relationships to be overestimated and may also lead to incorrect signs (Lim and Shumway, 1997).

48 Jorgenson's work suggests that the contribution of technical change has frequently been to reduce energy efficiency and thereby increase overall energy consumption, even while other factors (such as structural change) are acting to decrease it. Hence, not only is the direction of technical change opposite to what is conventionally assumed, but also opposite to what is required for an empirical estimate of the rebound effect. But technical change has clearly improved the thermodynamic conversion efficiency of individual devices, such as motors and boilers. What Jorgenson's work suggests, therefore, is this that has not necessarily translated into improvements in more aggregate measures of energy intensity at the level of industrial sectors. Similarly, the more robust results of Sue Wing and Eckhaus (2006) suggest that this has not necessarily translated into improvements in more aggregate measures of energy intensity for particular types of capital (e.g. machinery). Hence, the relevance of these results may hinge upon the appropriate choice of independent variable for the rebound effect.

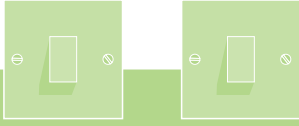


energy productivity have been associated with proportionally greater improvements in total factor productivity. While Schurr's work provides evidence for this at the level of the national economy, numerous examples from the energy efficiency literature provide comparable evidence at the level of individual sectors and technologies (Box 5.3). Such examples are frequently used by authors such as Lovins (1997) to support the business case for energy efficiency, but they also point to situations where rebound effects may be expected to be large (Saunders, 2000b). If energy efficient technologies boost total factor productivity and thereby

save more than energy costs alone, the argument that rebound effects must be small because the share of energy in total costs is small is undermined. Much the same applies to the contribution of energy efficiency improvements to economic growth. But this leaves open the question of whether energy efficiency improvements are necessarily associated with proportionally greater improvements in total factor productivity, or whether (as seems more likely) this is contingent upon particular technologies and circumstances. If the latter is the case, policy measures could potentially be targeted on 'dedicated' energy efficiency

Box 5.3 Examples from the energy efficiency literature of the link between improved energy efficiency and improved total factor productivity

- Lovins and Lovins (1997) used case studies to argue that better visual, acoustic and thermal comfort in well-designed, energy efficient buildings can improve labour productivity by as much as 16%. Since labour costs in commercial buildings are typically 25 times greater than energy costs, the resulting cost savings can potentially dwarf those from reduced energy consumption.
- Pye and McKane (1998) showed how the installation of energy efficient motors reduced wear and tear, extended the lifetime of system components and achieved savings in capital and labour costs that exceeded the reduction in energy costs.
- Sorrell *et al.* (2004) found a host of examples of the 'hidden benefits' of energy efficiency improvements within 48 case studies of organisational energy management. For example changes to defrosting regimes at a brewery led to energy savings, water savings, reduced maintenance and reduced deterioration of building fabric.
- Worrell *et al.* (2003) analysed the cost savings from 52 energy efficiency projects, including motor replacements, fans/duct/pipe insulation, improved controls and heat recovery in a range of industrial sectors. The average payback period from energy savings alone was 4.2 years, but this fell to 1.9 years when the non-energy benefits were taken into account.
- Using plant-level data, Boyd and Pang (2000) estimated fuel and electricity intensity in the glass industry as a function of energy prices, cumulative output, a time trend, capacity utilisation and overall productivity. Their results show that the most productive plants are also most energy efficient and that a 1% improvement in overall productivity results in a more than 1% improvement in energy efficiency.



improvements that have smaller impacts on total factor productivity and hence smaller rebound effects.

5.3 Energy productivity and production theory

Harry Saunders is the second major advocate of the 'Khazzoom-Brookes postulate' and has brought a new level of sophistication to the rebound debate by basing his arguments upon neoclassical production and growth theory. This work is abstract and theoretical and is necessarily based on highly restrictive assumptions that can be a focus of criticism. But Saunders does not claim that his results prove the K-B postulate, but merely provide suggestive evidence in its favour, given certain assumptions about how the economy operates. Most importantly, he shows how backfire is the predicted outcome of **standard** economic models.

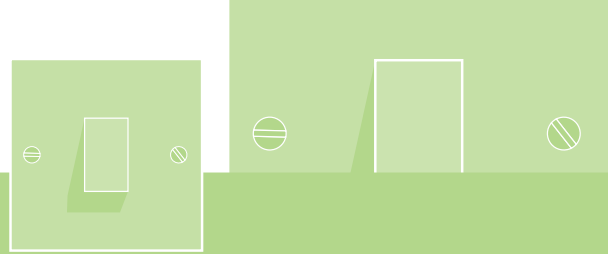
Saunders (1992) uses the neoclassical growth model to argue that backfire is a likely outcome of 'pure' energy efficiency improvements - that is, a form of technical change that improves energy productivity while not affecting the productivity of other inputs. He also argues that improvements in capital, labour or materials productivity will increase overall energy consumption. Since technical change typically improves the productivity of several inputs

simultaneously, Saunders argues that most forms of technical change will increase overall energy consumption.

Saunders' use of the neoclassical growth model was subsequently challenged by Howarth (1997), who argued that the failure to distinguish between energy and energy services led to the probability of backfire being overestimated. However, Saunders (2000a) subsequently demonstrated that backfire is still predicted by the neoclassical model when an alternative choice is made for the production function⁴⁹ used to provide energy services. In a more recent contribution, Saunders (2007) focuses on the potential of different types of production function to generate backfire. Unlike Saunders (1992), this work is also applicable to individual firms and sectors and opens up the possibility of using empirically estimated production functions to estimate the rebound effect from particular technologies in particular sectors (Saunders, 2005). Box 5.4 provides a very simple illustration of Saunders' approach and contrasts this with an alternative approach by Laitner (2000).

Saunders (2007) shows how the predicted magnitude of rebound effects depends almost entirely on the choice of the relevant production function - whether at the firm, sector or economy-wide level. Several commonly used production functions are found to be effectively useless in investigating the rebound

49 Production functions are normally represented by functional forms which are intended to approximate the relationship between inputs and outputs. Their purpose is to define a set of parameters which, given the observed data, reasonably approximate real-world production behaviour. This is useful in understanding the rate at which agents within an economy can feasibly (or have historically) moved between alternative input combinations. There are a range of different functional forms available and the appropriate choice involves trade-offs between flexibility and analytical tractability.



effect, since the relevant results are the same for whatever values are chosen for key parameters. One popular production function (the constant elasticity of substitution, or CES), is found to be able to simulate rebound effects of different magnitudes, but only if a particular assumption is made about how different inputs are combined.⁵⁰ Since this form is widely employed within energy-economic models, Saunders' results raise serious concerns about the ability of such models to accurately simulate rebound effects. An alternative and more flexible functional form (the 'translog') that is widely used in empirical studies is also found to lead to backfire once standard restrictions are imposed on the parameter values to ensure that the behaviour of the function is consistent with economic theory (Saunders, 2007)⁵¹.

There is a substantial empirical literature estimating the parameters of different types of production function at different levels of aggregation and obtaining a good fit with observed data. Hence, if such functions are considered to provide a reasonable representation of real-world economic behaviour, Saunders' work suggests that 'pure' energy-efficiency

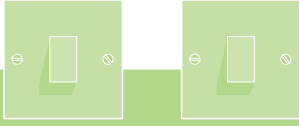
improvements are likely to lead to backfire. Alternatively, if rebound effects are considered to vary widely in magnitude between different sectors, Saunders' work suggests that standard and widely used economic methodologies cannot be used to simulate them.

The above conclusions apply to pure energy efficiency improvements. But Saunders (2005) also uses numerical simulations to demonstrate the potential for much larger rebound effects when improvements in energy efficiency are combined with improvements in the productivity of other inputs. Again, if the validity of the theoretical assumptions is accepted, these results suggest that backfire may be a more common outcome than is conventionally assumed.

Saunders approach is entirely theoretical and therefore severely limited by the assumptions implicit in the relevant models. For instance, technology always comes free, there are only constant returns to scale in production, markets are fully competitive, there is always full employment, qualitative differences in capital and energy are ignored and so on. Indeed, a considerable literature challenges the idea that an 'aggregate'

50 The CES function used by Saunders combines inputs into pairs, or 'nests'. For example, a nested production function with capital (K), labour (L) and energy (E) inputs, could take one of three forms, namely: K(LE); (KL)E; (KE)L. Saunders (1992) shows that the (KL)E form permits a range of values for the rebound effect (depending upon the elasticity of substitution between energy and capital/labour), while the other forms always lead to backfire. However, despite being in widespread use, this type of function imposes very restrictive conditions on real-world behaviour that are not supported by empirical evidence (Frondel and Schmidt, 2004).

51 Restrictions normally have to be imposed upon the parameter values in a translog cost function to ensure that its behaviour is consistent with basic economic theory. In particular, the cost function must be concave - implying that the marginal product of each input declines with increasing use of that input. In many applications, such as CGE modelling, these conditions need to be satisfied for all input combinations, but empirically estimated cost functions sometimes violate these conditions (Diewert and Wales, 1987). However, Ryan and Wales (2000) show that if concavity is imposed locally at a suitably chosen reference point, the restriction may be satisfied at most of the data points in the sample. Under these circumstances, the translog may be able to represent different types of rebound effect for particular data sets.



production function for the economy as a whole is meaningful concept (Fisher, 1993; Temple, 2006) - although this may not necessarily invalidate the use of such functions for representing the behaviour of individual sectors. A particular weakness is the assumption that technical change is costless and autonomous, without explicit representation of the processes that affect its rate and direction. This characteristic limits the capacity of such models to address many policy-relevant questions. More recent developments in so-called 'endogenous growth theory' have overcome this weakness to a large extent, but to date no authors have used such models to explore the rebound effect. However, since what is at issue is the consequences of energy efficiency improvements, the source of those improvements is arguably a secondary concern.

Overall, Saunders work suggests that significant rebound effects can exist in theory, backfire is quite likely and this result is robust to different model assumptions. Since these results derive from a contested theoretical framework, they are suggestive rather than definitive. But they deserve to be taken seriously.

5.4 Substitution between energy and capital

A key conclusion from Saunders' work is as follows:

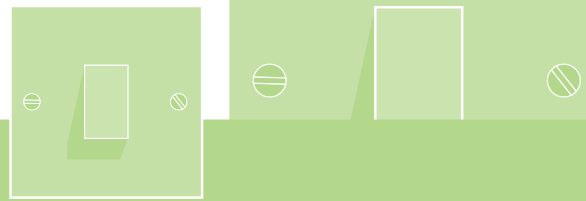
"It appears that the ease with which fuel can substitute for other factors of production (such as capital and labour) has a strong influence on how much

rebound will be experienced. Apparently, the greater this ease of substitution, the greater will be the rebound" (Saunders, 2000, p. 443).

The parameter that measures this 'ease' of substitution is the so-called *elasticity of substitution* between energy and other inputs (σ). High values of the *elasticity of substitution* between energy and other inputs mean that a particular sector or economy is more 'flexible' and may therefore adapt relatively easily to changes in energy prices. In contrast, low values of the elasticity of substitution between energy and other inputs suggest that increases in energy prices may have a disproportionate impact on productivity and growth. The elasticity of substitution is therefore a key parameter within energy-economic models, leading Saunders to suggest a possible trade off in climate policy:

"...If one believes σ is low, one worries less about rebound and should incline towards programmes aimed at creating new fuel efficient technologies. With low σ carbon taxes are less effective in achieving a given reduction in fuel use and would prove more costly to the economy. In contrast, if one believes σ is high, one worries more about rebound and should incline towards programmes aimed at reducing fuel use via taxes. With high σ , carbon taxes have more of an effect at lower cost to the economy." (Saunders, 2000b)

These observations suggest that a closer examination of the nature, determinants and typical values of elasticities of substitution between energy and other inputs could provide some insights into



Box 5.4 How theoretical assumptions can determine results

Much of Saunders work involves the use of calculus to investigate the behaviour of neoclassical production functions. A very simple, but still widely used production function is the 'Cobb- Douglas', which may be represented as follows: $Y = aK^\alpha L^\beta (\tau E)^{1-\alpha-\beta}$

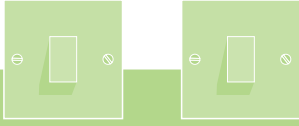
Where: K=capital, L=labour, E=energy and $\alpha+\beta=1$. The multiplier $\tau(\tau \geq 1)$ increases the productivity of energy inputs, so that the product τE represents 'effective' energy inputs. This may be interpreted as a form of technical change that does not affect the productivity of other inputs and is assumed to be costless. Saunders (2007) investigates the effect of improvements in energy productivity (τ) on energy consumption and economic output in the short-term, with real energy prices fixed. He finds that, with a Cobb-Douglas function, both energy consumption and output increase by the same amount, leaving the aggregate energy/output ratio **unchanged**. The improvement in the productivity of energy inputs (τ) has therefore led to backfire, since economy-wide energy consumption has increased. Using standard assumptions about the share of energy in total costs, Saunders (2000a) estimates that a 20% increase in the productivity of energy inputs should only increase GDP by some 2.3%.

This approach can be compared with Laitner's (2000) 'back of the envelope' estimate of the effect of energy efficiency improvements on the US economy. This simply **assumes** that energy efficiency policies would reduce the economy-wide energy/GDP ratio by 30%. As a result, the only rebound effects that Laitner considers are the effect of energy efficiency improvements on GDP growth. Since the share of energy in total costs is small, the additional economic growth stimulated by 'pure' energy efficiency improvements should be insufficient to offset the energy savings achieved by the reduction in the energy/GDP ratio. Laitner shows that this conclusion is unchanged when possible changes in energy prices are also taken into account.

Both authors agree, therefore, that 'pure' energy efficiency improvements should have a relatively small impact on GDP. But while Laitner uses this result to argue that backfire is unlikely, Saunders position is that backfire is likely to be the norm.

These conflicting conclusions result in part from differences in approach, and in part from different definitions of the independent variable. Saunders uses an improvement in energy productivity as the independent variable and derives a result in which the economy-wide energy/GDP ratio remains unchanged (i.e. energy consumption and economic output increase by the same amount). Laitner, in contrast, uses the economy-wide energy/GDP ratio as the independent variable and simply assumes that energy efficiency policies will reduce this by 30% - thereby ignoring any 'lower-level' rebound effects from these policies. A criticism of Saunders approach could be that the real-world economy is unlikely to behave in the manner suggested by a Cobb-Douglas production function. But Saunders (2007) shows that several alternative and more flexible assumptions about the form of the production function also lead to backfire. In contrast, a criticism of Laitner's approach could be that the assumption that energy efficiency policies will reduce the energy/GDP ratio by this amount is flawed.

Hence, while both approaches are internally consistent, their results are driven by conflicting theoretical assumptions that require empirical validation.



the likely magnitude of rebound effects in different sectors and for the economy as a whole. Of particular interest is the elasticity of substitution between energy and capital, since many types of energy efficiency improvement may be understood as the substitution of capital for energy. *Technical Report 3* therefore provides an in-depth examination of empirical estimates of the elasticity of substitution between energy and capital, together with an extensive review of the associated theoretical issues. The empirical literature on this subject turns out to be confusing and contradictory, with more than three decades of empirical research failing to reach a consensus on whether energy and capital may be considered as 'substitutes' or 'complements' (Box 5.5 and 5.6). Moreover, the relationship between the elasticity of substitution and the rebound effect turns out to be far from straightforward.

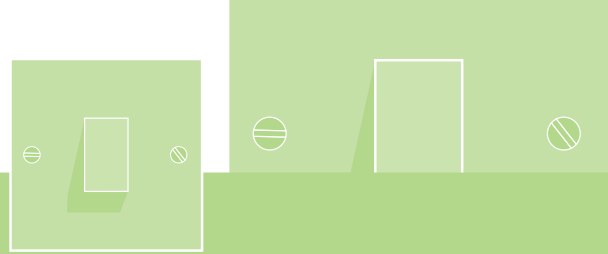
Our investigation of this topic reveals that Saunders' statements regarding the relationship between elasticities of substitution and the rebound effect are potentially misleading. The relationship depends very much upon the distinction between energy and energy services, the particular choice of production function, the appropriate definition of the elasticity of substitution and the validity of the assumption of 'separability' between energy services and other inputs (Box 5.5). When these are taken into account, it is found that large rebound effects may occur even when the elasticity of substitution between energy and capital is low, which appears to contradict the observation quoted at the beginning of

this section. The possible trade-off in climate policy that is suggested by Saunders may therefore not exist. In addition, since most empirical studies measure something quite different from the parameters assumed within energy-economic models, the empirical basis for those models is further called into question (Box 4.4).

To the extent that a general conclusion can be drawn from the empirical literature, it is that energy and capital typically appear to be either complements or weak substitutes (Box 5.6). This could have some important implications. First, a reduction in the price of capital relative to energy (e.g. through investment subsidies) may in some circumstances increase energy consumption rather than reduce it (Berndt and Wood, 1979). Second, the economic impact of an increase in energy prices could be significant:

"A reduction in the use of energy by itself will have a relatively small economic impact, determined to first order by energy's small value share. But if the reduced use of energy also produces a reduction in the use of capital, the larger value share of capital applies and the economic impact is magnified. This indirect effect through capital can be the largest component of the economic impact of reduced energy use... but this effect is often ignored in economic impact analyses of energy policy" (Hogan, 1979)

Hence, this review suggests the possibility of a strong link between energy consumption and economic output as well as potentially high costs associated with reducing energy consumption. However,



Box 5.5 Defining and measuring elasticities of substitution

There are at least five definitions of the elasticity of substitution in common use and several others that appear less frequently. The lack of consistency in the use of these definitions and the lack of clarity in the relationship between them, combine to make the empirical literature both confusing and contradictory (Stern, 2004a).

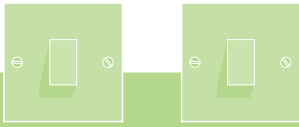
For all definitions, substitution between two inputs is 'easier' when the magnitude of the elasticity of substitution between them is greater, while the sign of the elasticity of substitution is commonly used to classify inputs as 'substitutes' or 'complements'. But the appropriate classification depends upon the particular definition being used (i.e. inputs may be substitutes under one measure and complements under another).

The majority of existing empirical studies use the sign of the 'Allen-Urzza' elasticity of substitution (*AES*) to make this classification. With this definition, two inputs are described as substitutes (complements) when the usage of one increases (decreases) when the price of the other increases (decreases), holding output constant. However this measure has a number of acknowledged drawbacks and its quantitative value lacks meaning (Fronzel, 2004). In many cases, the Cross Price elasticity (*CPE*) or the Morishima elasticity of substitution (*MES*) would be more appropriate measures, but these have yet to gain widespread use.

A large number of empirical studies estimate elasticities of substitution between different inputs within different sectors and countries and over different time periods. These rely upon a variety of assumptions, including in particular the specific form of the production or cost function employed. In general, the *actual* scope for substitution may be expected to vary widely between different sectors, different levels of aggregation and different periods of time, while the estimated scope for substitution may depend very much upon the particular methodology and assumptions used.

Standard methodological approaches frequently assume that the ease of substitution between two inputs is unaffected by the level or price of other inputs ('separability'). This assumption is not always tested, and even if it is found to hold, the associated estimates of the elasticity of substitution between two inputs in the same group could still be biased (Fronzel and Schmidt, 2004). Assumptions about the nature and bias of technical change may also have a substantial impact on the empirical results, but distinguishing between technical change and price-induced substitution is empirically challenging.

The level of aggregation of the study is also important, since a sector may still exhibit input substitution in the aggregate due to changes in product mix, even if the mix of inputs required to produce a particular product is relatively fixed. Many studies overlook such changes and implicitly assume that the product mix is fixed (Miller, 1986). Since the scope for changing product mix is greater at higher levels of aggregation, the estimated scope for input substitution may also be greater when higher levels of aggregation are used (Solow, 1987). However, individual inputs cannot always be considered as independent, notably because energy is required for the provision of labour and capital. Substitution of capital for energy and one sector, for example, may lead to an increase in energy consumption in the sector providing the relevant capital. This suggests that the estimated scope for input substitution may be smaller when higher levels of aggregation are used. These two factors may therefore partly cancel each other out.

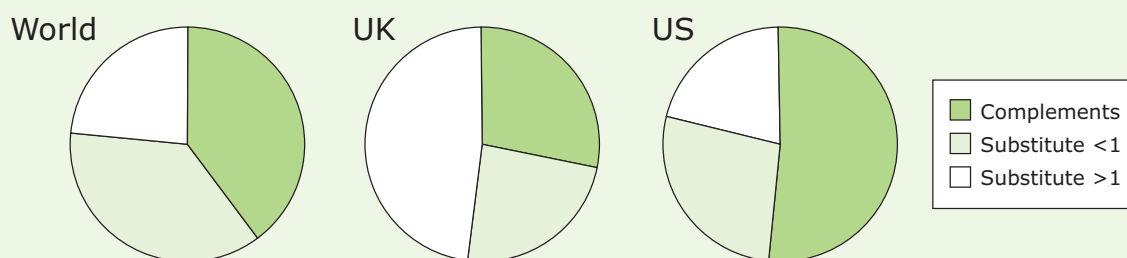


Box 5.6 Empirical estimates of the elasticity of substitution between energy and capital

Technical Report 3 reviews more than 200 empirical estimates of the elasticity of substitution between energy and capital. The results were analysed to see how the estimates varied with factors such as the sectors covered, the functional form employed, the use of time-series versus cross-sectional data and the assumptions regarding technical change. The most striking result from the analysis is the lack of consensus that has been achieved to date, despite three decades of empirical work. While this may be expected if the degree of substitutability depends upon the sector, level of aggregation and time period analysed, it is notable that several studies reach different conclusions for the same sector and time period, or for the same sector in different countries.

If a general conclusion can be drawn, it is that *energy and capital typically appear to be either complements (i.e. $AES < 0$) or weak substitutes (i.e. $0 < AES < 0.5$)*. However, little confidence can be placed in this conclusion, given the diversity of the results and their apparent dependence upon the particular specification and assumptions used. While there appears to be some agreement on the possible causes of the different results, there is no real consensus on either the relative importance of different causes or the likely direction of influence of each individual cause (i.e. whether a particular specification/assumption is likely to make the estimate of the substitution elasticity bigger or smaller).

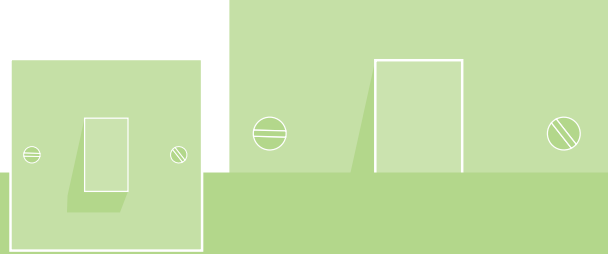
Overall summary of results



given the extent to which the estimated scope for substitution varies between different sectors and levels of aggregation (not to mention between different fuels and types of capital), broad conclusions of this type could be misleading. Moreover, given the difficulties with the empirical literature, very little confidence can be placed in this result.

5.5 Energy productivity and ecological economics

In his 1984 paper, Brookes quotes Sam Schurr's observation that: "...it is energy that drives modern economic systems rather than such systems creating a demand for energy." (Brookes, 1984). This highlights an important theme in Brookes' work: namely that energy plays



a more important role in economic growth than is conventionally assumed by neoclassical economists. But precisely the same claim is made by ecological economists such as Cleveland, *et al.* (1984), who attribute a large component of the increased productivity over the past century to the increasing availability of high-quality energy sources. This leads them to express scepticism over the scope for decoupling economic growth from increased energy consumption.

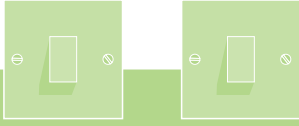
Ecological economists have not directly investigated the rebound effect, but their work arguably provides suggestive support for the K-B postulate in much the same way as Schurr's research on the historical determinants of US productivity growth. Four examples of this work are briefly described below.

First, analysis by Kaufmann (1992; 2004) and others suggests that historical reductions in energy/GDP ratios owe much more to structural change and improvements in energy quality than to technological improvements in energy efficiency (Box 5.7). By neglecting changes in energy quality, conventional analysts may have come to incorrect conclusions regarding the rate and direction of technical change and its contribution to reduced energy consumption. Kaufmann (1992) suggests that, not only does the energy/GDP ratio reflect the influence of factors *other* than energy-saving technical change, but these other factors may be *sufficient* to explain the observed trends. Hence, the observed improvements in the thermodynamic efficiency of individual devices at the micro level do not appear to have significantly contributed to the observed

reduction in energy intensity at the macro-level. As with the work of Jorgenson and others on energy-using technical change, this suggests that the conventional assumptions of energy-economic models may be flawed.

Second, both neoclassical and ecological economists have used modern econometric techniques to test the direction of causality between energy consumption and GDP (Stern, 1993; Chontanawat, *et al.*, 2006; Lee, 2006; Yoo, 2006; Zachariadis, 2006). If GDP growth is the cause of increased energy consumption then a change in the growth rate should be followed by a change in energy consumption and vice versa. It is argued that if causality runs from GDP to energy consumption then energy consumption may be reduced without adverse effects on economic growth, while if causality runs the other way round a reduction in energy use may negatively affect economic growth. While the results of such studies are frequently contradictory, most of them neglect changes in energy quality. When energy quality is taken into account, the causality appears to run from energy consumption to GDP - as ecological economists suggest (Stern, 1993; 2000).

Third, historical experience provides very little support for the claim that increases in income will lead to declining energy consumption (Stern, 2004b; Richmond and Kaufmann, 2006b; 2006a). While the income elasticity of aggregate energy consumption may be both declining and less than one in OECD countries, there is no evidence that it is negative (or is soon to become negative). Again, neglect of changes in fuel mix and energy prices



Box 5.7 Energy/GDP ratios and changes in energy quality

Kaufmann (1992) sought to quantify the factors that contributed to changes in the ratio of primary energy consumption (in kWh thermal) to real GDP in France, Germany, Japan and the UK during the period 1950-1990. The explanatory variables were the percentage share of different energy carriers in primary energy consumption; the fraction of GDP spent directly on energy by households; the proportion of the product mix that originated in energy intensive manufacturing sectors; and primary energy prices.

Despite the simplicity of this formulation, it was found to account for most of the variation in energy intensity for the four countries studied throughout the post-war period. Kaufmann argued that improvements in energy quality led to lower energy intensities by allowing more useful work to be obtained from each heat unit of energy input. The shift from coal to oil contributed greatly to declining energy/GDP ratios prior to 1973, while the rising contribution of primary electricity (hydro and nuclear) provided a significant contribution after 1973.

Since the energy intensity of household energy purchases is an order of magnitude greater than the energy intensity of other goods and services, falls in the former as a fraction of total expenditure should translate into falls in the energy/GDP ratio – and vice versa. The fraction of GDP spent directly on energy by households increased prior to 1973 and decreased thereafter and these trends were also found to be highly significant in explaining trends in the aggregate ratio.

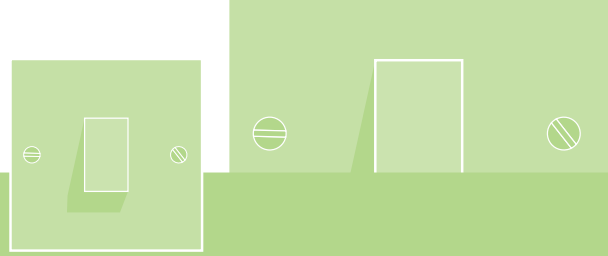
In addition, changes in energy prices encouraged substitution between inputs, including the substitution of capital for energy, while shifts towards less energy intensive manufacturing sectors and towards the service sector reduced energy/GDP ratios. These mechanisms were found to be less important than those above, but when all four factors were taken into account, they were found to provide a more or less sufficient explanation for the observed trends in energy intensity.

By implication, Kaufmann's results suggest little role for energy-saving technical change - defined as advances in technology that allow the same type and quantity of output to be produced with less energy inputs. Kaufmann tested this implication in three different ways,⁵² but in each case failed to find statistically significant evidence for energy saving technical change. Kaufmann comments that "...Technical changes has reduced the amount of energy (as measured in heat units) used to produce a unit of output. But characterising that technical change as 'energy-saving' is misleading. Over the last 40 years, technical change has reduced the amount of energy use to produce a unit of output by developing new techniques for using oil, natural gas and primary electricity in place of coal."

Kaufmann also interprets the results as illustrating the limited scope, at the level of the macro-economy, for substituting capital and labour for energy. Estimated annually, the own price elasticity of energy demand varies between -0.05 and -0.39, which is generally smaller than the elasticities estimated at the level of individual sectors. This arguably suggests that the indirect energy consumption associated with labour and capital inputs constitute a significant portion of the energy saved directly through energy efficiency improvements in each of those sectors.

The results also indicate that reducing the fraction of GDP spent directly on energy by households, may be the most effective way of reducing the energy/GDP ratio. This in turn suggests that rebound effects from energy efficiency improvements may be lower in the household sector than in producing sectors.

⁵² Namely: a) seeking evidence for serial correlation and heteroscedasticity in the error term, which could be evidence of missing variable bias; b) including a time trend to represent energy-saving technical change; and c) using dummy variables to test for changes in the intercept or slope of individual regression coefficients during different time periods - such as may follow an increase in energy prices if this induces energy saving technical change.



may have led earlier studies to draw misleading conclusions regarding the role and potential of energy saving technical change (Kaufmann, 2004).

Finally, ecological economists have developed a number of alternatives to the conventional models of economic growth (Kummel, *et al.*, 1985; Beaudreau, 1998; Kummel, *et al.*, 2000; Ayres and Warr, 2005). A key feature of these models is a departure from the traditional assumption that the productivity of each input is proportional to the share of that input in the value of output. Instead, the productivity of each input is estimated directly from a production function. These models are found to reproduce historical trends in economic growth extremely well, without attributing any role to technical change. This is in contrast to conventional theories of economic growth, which attribute much of the increase in output to technical change.⁵³ The marginal productivity of energy inputs is found to be around ten times larger than its cost share, implying that improvements in the productivity of energy inputs could have a dramatic effect on economic growth and therefore on economy-wide energy consumption – in other words, the rebound effect could be very large.

Of particular interest is the work by Ayres and Warr (2005), who combine historical data on the exergy content of fuel inputs and thermodynamic (second-law) conversion efficiencies (Table 5.2) to

develop a unique time series of the exergy output of conversion devices (termed useful work) in the US economy over the past century. They show that useful work inputs to the US economy have grown by a factor of 18 over the past 100 years, implying that the useful work obtained from fuel resources has grown much faster than the consumption of fuels themselves, owing to substantial improvements in thermodynamic conversion efficiencies. This approach makes a great deal of sense, since it useful work that is economically productive, while the exergy that is lost in conversion processes is effectively wasted (Ayres and Warr, 2006).

By including useful work in their production function, rather than primary energy, Ayres and Warr obtain an extremely good fit to US GDP trends over the past century, thereby eliminating the need for a multiplier for technical change. The implication is that improvements in thermodynamic conversion efficiency provide a quantifiable surrogate for all forms of technical change that contribute to economic growth. Far from being a minor contributor to economic growth, improvements in thermodynamic efficiency become the dominant driver – obviating the need for alternative measures of technological change.

While firmly outside mainstream economics, the ecological perspective is well articulated and persuasive. The

53 Traditional neoclassical growth models estimate 'technical change' as the residual growth in output that is not explained by the growth of inputs. Early growth models attributed as much as 70% of the growth in output to technical change, but later studies have shown how the proportion of growth that is attributed to technical change depends upon how the inputs are measured (Jorgenson and Griliches, 1967). In neoclassical growth models, technical change is typically represented by a simple time trend. Modern theories of economic growth seek to make the source and direction of technical change endogenous.

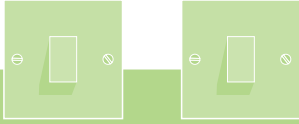


Table 5.2 Trends in second-law conversion efficiencies of primary conversion processes in the US (average % efficiency in specified year)

Year	Electricity generation and distribution	Transportation	High temperature process heat (steel)	Medium temperature process heat (steam)	Low temperature space heat
1900	3.8	3.0	7	5	0.25
1970	32.5	8.0	20	14	2
1990	33.3	13.9	25	20	3

Source: Ayres *et al.* (2003)

general implication is that energy is more productive than is suggested by its small share of total costs. This is precisely the argument that Schurr made and which appears to underlie Brookes' arguments in favour of backfire. However, the empirical evidence in support of this perspective remains patchy and in some cases flawed. For example, the results of econometric investigations of causality relationships between energy and GDP remain ambiguous and the policy implications that are drawn are frequently oversimplified (Zachariadis, 2006). Also, the statistical form of causality that is being measured here (so-called 'Granger causality') is not the same as causality as conventionally understood⁵⁴ and conventional notions of causality may be problematic for systems as complex as modern economies. In a similar manner, the different variants of 'ecological growth models' rely upon an unusual and oddly

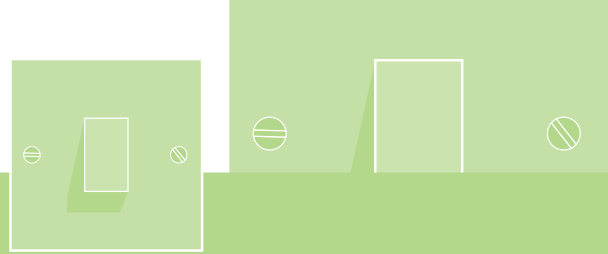
behaved production function⁵⁵, provide results that are difficult to reconcile with each other⁵⁶ and appear vulnerable to bias from a number of sources⁵⁷ that could potentially invalidate the results. As a result, claims that the marginal productivity of energy is an order of magnitude larger than its cost share, or that improvement in thermodynamic conversion efficiency can act as a suitable proxy for technical change, must be treated with considerable caution.

Unfortunately, the different assumptions of conventional and ecological perspectives seem to have prevented an objective comparison of their methods and conclusions. Convincing evidence of the disproportionate contribution of energy to economic growth therefore remains elusive. Moreover, even if this were to be accepted, the link from this evidence to the K-B postulate remains ambiguous and indirect.

54 For example, a met office prediction of rain can be shown to 'Granger cause' rain!

55 The so-called LINEX production function implies increasing marginal returns and variable marginal productivities.

56 Ayres and Warr (2005) claim that the inclusion of useful work rather than primary energy in the production function allows them to dispense with a separate time trend to represent technical change. But they made no comment as to why Kummel (1985; 2000) is able to reproduce economic growth without a time trend, while measuring energy inputs on the basis of thermal content.



The neoclassical assumption appears to be that capital, labour and energy inputs have *independent* and *additive* effects on economic output, with any residual increase being attributed to exogenous technical change. Endogenous growth theory has modified these assumptions, but still attributes a relatively minor role to energy. In contrast, the ecological assumption appears to be that capital, labour and energy are *interdependent* inputs that have *synergistic* and *multiplicative* effects on economic output, and that the increased availability of low-cost, high-quality energy sources provides a necessary condition for technical change. A bridge between the two could potentially be provided by Toman and Jemelkova's (2003) observation that increased inputs of useful work (or energy services) may *enhance* the productivity of capital and labour:

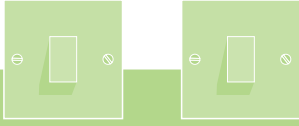
".....when the supply of energy services is increased, there is not just more energy to be used by each skilled worker or machine; the productivity with which every unit of energy is used also rises. If all inputs to final production are increased in some proportion, final output would grow in greater proportion because of the effect on non-energy inputs." (Toman and Jemelkova, 2003)

Focusing in particular on households in developing countries, Toman and Jemelkova (2003) propose a number of ways in which the increased availability of useful work could improve capital and labour productivity and hence disproportionately affect economic output. For example, cheaper and better lighting could allow greater flexibility in time allocation throughout the day and evening and enhance the productivity of education

efforts. The increased availability of electricity could promote access to safe drinking water (e.g. in deeper wells), allow the refrigeration of food and medicine and thereby improve both the health of workers and their economic productivity. Similarly, the increased availability of low-cost transport fuels could interact with investment in transport infrastructure to increase the geographic size, scale and efficiency of markets. Schurr's (1983; 1984; 1985) account of the impact of electricity (and especially electric motors) on the organisation and productivity of US manufacturing provides an analogous example for producers in developed countries.

It is an empirical question as to whether such benefits apply in practice and to what extent. Ecological economists appear to claim that such a situation is the norm, with the result that the increased availability of high-quality energy has been a primary driver of economic activity. But if the increased availability of high-quality energy inputs has a disproportionate impact on productivity and economic growth, then improvements in thermodynamic efficiency may do the same, because both increase the useful work available from conversion devices. If it is useful work rather than raw energy (or exergy) inputs that drives economic activity, then improvements in second-law conversion efficiency could potentially mitigate the economic impact of future shortages of high-quality forms of energy – notably oil.

However, this argument uses a thermodynamic measure of energy quality and therefore neglects the other factors that determine the economic productivity



of energy carriers. Also, improvements in conversion efficiencies are necessarily associated with embodied energy and are ultimately constrained by thermodynamic limitations; hence, their ability to compensate for future supply shortages may be limited. Moreover, if these improvements have a disproportionate effect on economic output, they may also be associated with large secondary effects.

5.6 Implications

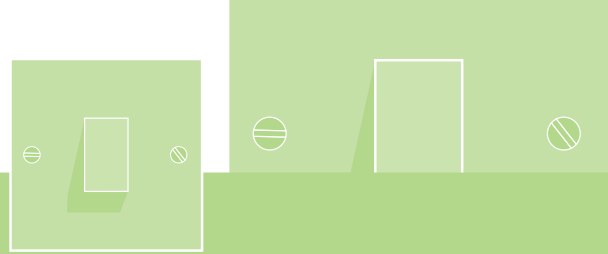
One interpretation of the K-B postulate is that *all* economically justified energy efficiency improvements will increase energy consumption above where it would be without those improvements. This is a counterintuitive claim for many people and therefore requires strong supporting evidence if it is to gain widespread acceptance. The main conclusion from the review is that such evidence does not exist. The theoretical and empirical evidence cited in favour of the postulate is suggestive rather than definitive, only indirectly relevant to the rebound effect and flawed in a number of respects. Nevertheless, the arguments and evidence deserve more serious attention than they have received to date. Much of the evidence points to economy-wide rebound effects being larger than is conventionally assumed and to energy playing a more important role in economic growth than is conventionally assumed.

The possibility of large economy-wide rebound effects has been dismissed by a number of leading energy analysts (Howarth, 1997; Lovins, 1998; Laitner,

2000; Schipper and Grubb, 2000). But it becomes more plausible if it is accepted that energy efficiency improvements are frequently associated with improvements in the productivity of other inputs. If this is the case, then rebound effects need not necessarily be small just because the share of energy in total costs is small. Future research should therefore investigate the extent to which improvements in energy efficiency (however defined and measured) are associated with broader improvements in economic productivity, and the circumstances under which economy-wide rebound effects are more or less likely to be large. For example, we may speculate that rebound effects should be larger for energy efficiency improvements associated with:

- energy intensive production sectors compared to non-energy intensive sectors;
- energy supply industries compared to energy users;
- core process technologies compared to non-core technologies;
- technologies in the early stages of diffusion compared to those in the later stages; and
- technologies that improve capital and labour productivity, compared to those that do not.

Rebound effects may be particularly large for the energy efficiency improvements associated with 'general-purpose technologies', such as steam engines, railroads, automobiles and computers. General-purpose technologies (GPTs)



have a wide scope for improvement and elaboration, are applicable across a broad range of uses, have potential for use in a wide variety of products and processes and have strong complementarities with existing or potential new technologies (Lipsey, *et al.*, 2005). Steam engines provide a paradigmatic illustration of a GPT in the 19th-century, while electric motors provides a comparable illustration for the early 20th century. The former was used by Jevons to support the case for backfire, while the latter was used by Brookes.

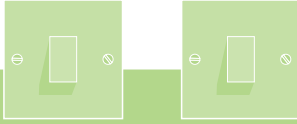
The key to unpacking the K-B postulate may therefore be to distinguish the energy efficiency improvements associated with GPTs from other forms of energy efficiency improvement. The K-B postulate seems more likely to hold for the former, particularly when these are used by producers and when the energy efficiency improvements occur at an early stage of development and diffusion of the technology. The opportunities offered by these technologies have such long term and significant effects on innovation, productivity and economic growth that economy-wide energy consumption is increased. In contrast, the K-B postulate seems less likely to hold for dedicated energy efficiency technologies such as improved thermal insulation, particularly when these are used by consumers or when they play a subsidiary role in economic production. These technologies have smaller effects on productivity and economic growth, with the result that economy-wide energy consumption may be reduced.

The implication is that energy policy should focus on encouraging dedicated

energy efficient technologies, rather than improving the energy efficiency of GPTs. However, these categories are poorly defined and the boundaries between them are blurred. Moreover, even if GPTs can meaningfully be distinguished from other forms of technology, continued economic growth is likely to depend upon the diffusion of new types of GPT that may increase aggregate energy consumption. Hence, while it may be unlikely that all energy efficiency improvements will lead to backfire, we still have much to learn about the factors that make backfire more or less likely.

5.7 Summary

- The case for the K-B postulate is not based upon empirical estimates of rebound effects, but instead relies upon stylised theoretical arguments and empirical evidence from a range of sources that is both suggestive and indirect. Disputes over the postulate rest in large part on competing theoretical assumptions.
- Historical experience demonstrates that substantial improvements in various measures of energy efficiency have occurred alongside continuing increases in economic output, total factor productivity and overall energy consumption. However, the causal links between these trends remains unclear.
- Brookes has developed a range of arguments in support of the K-B postulate and cited a number of suggestive sources of empirical evidence. However, his theoretical



arguments have a number of weaknesses and more recent empirical evidence does not always support his case.

- A key theme in Brookes' work is that improvements in energy productivity are generally associated with proportionally greater improvements in total factor productivity. Evidence for this can be found at the level of national economies, as well as individual sectors and technologies. If energy efficient technologies boost the productivity of other inputs and thereby save costs on more than energy alone, the argument that rebound effects must be small because the share of energy in total costs is small is undermined. But this leaves open the question of whether this is necessarily the case, or whether it is contingent upon particular circumstances.
- Saunders has shown how backfire is the predicted outcome of neoclassical production functions that are used widely in theoretical and empirical research. If such functions are considered to provide a reasonable representation of real-world behaviour, Saunders' work suggests that 'pure' energy-efficiency improvements are likely to lead to backfire. Alternatively, if rebound effects vary widely in magnitude between different sectors, such functions cannot be used to represent them. In either case, the implications are far-reaching.
- Rebound effects depend in part upon the scope for substitution between energy and other inputs, but the nature of this relationship is more complex than commonly assumed. The extensive empirical literature in this area is both confused and inconclusive and provides an insufficient basis for the assumed parameter values within energy-economic models. To the extent that general conclusions can be drawn, it is that capital and energy appear to be complements or only weak substitutes. This suggests the possibility of a strong link between energy consumption and economic output and high costs associated with reducing energy consumption.
- Underlying Brookes' work is a claim about the contribution of energy to economic growth. Most economists assume that the increased availability of energy inputs has only made a small contribution to economic growth, owing to the small share of energy in total costs. In contrast, ecological economists argue that the increased availability and quality of energy inputs has been the primary driver of economic growth. But energy is only economically productive because it provides useful work. Hence, if increases in energy inputs contribute disproportionately to economic growth, then improvements in thermodynamic efficiency should do the same, since both provide more useful work. The dispute over the K-B postulate can therefore be linked to the much broader question of the

contribution of energy to economic growth.

- Ecological economists cite a range of evidence in support of their claims, but this remains patchy and in some cases flawed. Of particular interest are the alternatives to standard models of economic growth which can be used in support of claims that energy efficiency improvements are associated with substantial improvements in total factor productivity and that rebound effects are large. However, since these models have a number of theoretical and empirical weaknesses, convincing evidence of the disproportionate contribution of energy remain elusive.
- The debate over the K-B postulate would benefit from further distinctions between different types of energy

efficiency improvement. In particular, the K-B postulate seems more likely to hold for energy efficiency improvements associated with the early stage of diffusion of 'general-purpose technologies', such as electric motors in the early 20th century. It may be less likely to hold for the later stages of diffusion of these technologies, or for 'dedicated' energy efficiency technologies such as improved thermal insulation. However, these categories are poorly defined and the boundaries between them are blurred.

- Overall, while it is unlikely that all energy efficiency improvements will lead to backfire, we still have much to learn about the factors that make backfire more or less likely to occur.





6. Conclusions, research needs and policy implications

6.1 Conclusions

The main conclusions from this assessment are as follows:

1. Rebound effects are significant, but they need not make energy efficiency policies ineffective in reducing energy demand

- The available evidence for all types of rebound effects is limited and inconclusive. While the evidence is better for direct effects than for indirect effects, it remains mainly focused on a small number of consumer energy services within OECD countries. Both direct and indirect rebound effects appear to vary widely between different technologies, sectors and income groups and in most cases cannot be quantified with much confidence.
- The evidence does not suggest that improvements in energy efficiency routinely lead to economy-wide increases in energy consumption, as some commentators have suggested. At the same time the evidence does not suggest that economy-wide rebound effects are small (e.g. <10%) as many analysts and policymakers assume. Rebound effects therefore need to be taken seriously in policy appraisal.

2. For most consumer energy services in OECD countries, direct rebound effects are unlikely to exceed 30%

- Evidence for the direct rebound effect for personal automotive transport, household heating and household

cooling within OECD countries is relatively robust. Evidence for direct rebound effects for other consumer energy services is much weaker, as is that for energy efficiency improvements by producers.

- For household heating, household cooling and personal automotive transport in OECD countries, the direct rebound effect is likely to be less than 30% and may be closer to 10% for transport. Moreover, direct rebound effects for these energy services are expected to decline in the future as demand saturates and income increases. This means that improvements in energy efficiency should achieve 70% or more of the expected reduction in energy consumption for those services - although the existence of indirect effects means that the economy-wide reduction in energy consumption will be less. Direct rebound effects should be smaller for other consumer energy services where energy forms a relatively small proportion of total costs and therefore has little influence on operating decisions.
- These conclusions are subject to a number of important qualifications, including the dependence of direct rebound effects on household income, the neglect of 'marginal consumers' and the relatively limited time periods over which these effects have been studied
- There are very few studies of direct rebound effects from energy efficiency improvements in developing countries. However, both theoretical



considerations and the limited evidence that is available suggest that direct rebound effects in these contexts could be larger than in OECD countries and could in some cases exceed unity. This is especially the case for the 1.6 billion households who currently lack access to electricity and the 2.5 billion who rely upon biomass for cooking.

3. There are relatively few quantitative estimates of indirect and economy-wide rebound effects, but several studies suggest that economy-wide effects may exceed 50%

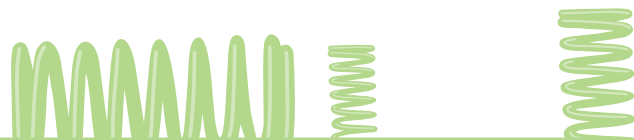
- Quantitative estimates of indirect and economy-wide rebound effects are rare. While a number of methodological approaches can be used to estimate these effects, the limited number of studies available provides an insufficient basis to draw any general conclusions. The most important insight from these studies is that the magnitude of the effect depends very much upon the sector with the energy efficiency improvement takes place and is sensitive to a number of variables.
- A handful of CGE modeling studies estimate economy-wide rebound effects to be 37% or more, with half of the studies predicting backfire. These effects derive from 'pure' energy efficiency improvements by producers (not consumers) and therefore do not rely upon simultaneous improvements in the productivity of other inputs. However, the small number of studies available,

the diversity of approaches used and the variety of methodological weaknesses associated with the CGE approach all suggest the need for caution when interpreting these results.

- In principle, more robust estimates of the economy-wide rebound effect may be obtained from macro-econometric models of national economies. Barker and Foxon (2006) use this approach to estimate an economy-wide rebound effect of 26% from current UK energy efficiency policies. However, there are a number of reasons why this study could have underestimated economy-wide effects.

4. The evidence and arguments used in support of the Khazzoom-Brookes postulate are insufficient to demonstrate its validity, but nevertheless pose an important challenge to conventional wisdom

- The theoretical arguments for the K-B postulate rely upon a conceptual framework that is stylised and restrictive, while the empirical evidence cited in its favour is indirect and suggestive. Since a number of flaws have been found with both, the K-B 'hypothesis' cannot be considered to have been adequately verified. Nevertheless, the arguments and evidence used to defend the K-B postulate deserve more serious attention than they have received to date.
- It is conventionally assumed that there is considerable scope for



substituting capital and other inputs for energy consumption while maintaining the same level of economic output. It is also conventionally assumed that technical change has historically improved the energy efficiency of individual sectors and thereby contributed to the observed decoupling of energy consumption from economic growth. However, the evidence reviewed in this report suggests that there is more limited scope for substituting other inputs for energy and that much technical change has acted to increase energy intensity. Also, once different fuels are weighted by their relative 'quality' or economic productivity, there is less evidence that the growth in economic output has been decoupled from the growth in energy consumption. Overall, this evidence points to economy-wide rebound effects relatively large and to energy playing a more important role in economic growth than is conventionally assumed.

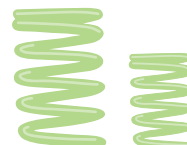
- The possibility of large economy-wide rebound effects becomes more plausible if it is accepted that energy efficiency improvements are frequently associated with proportionately greater improvements in total factor productivity. If this is the case, then rebound effects need not necessarily be small just because the share of energy in total costs is small. But energy efficiency improvements may not necessarily be associated with such improvements. Instead, the link between the two seems more likely to be contingent

upon particular technologies and circumstances.

- The debate over the K-B postulate would benefit from more careful distinctions between different types of energy efficiency improvement. For example, the K-B postulate seems more likely to hold for energy efficiency improvements associated with 'general-purpose technologies' (GPTs), particularly when these are used by producers and when the improvements occur at an early stage of development and diffusion. Steam engines provide a paradigmatic illustration of a GPT in the 19th-century, while electric motors provide a comparable illustration for the early 20th century. The opportunities offered by these technologies have such long term and significant effects on innovation, productivity and economic growth that economy-wide energy consumption is increased. In contrast, the K-B postulate seems less likely to hold for dedicated energy efficiency technologies such as thermal insulation, particularly when these are used by consumers. These technologies have smaller effects on productivity and economic growth, with the result that economy-wide energy consumption may be reduced.

6.2 Research needs

Given the potential importance of rebound effects, the evidence base is remarkably weak. While this is partly a consequence of the inherent difficulty of measuring or estimating such effects, there is



considerable scope for improving knowledge in a number of areas. The following highlights some priorities for future research.

1. Research on direct rebound effects needs to improve in rigour and expand in scope

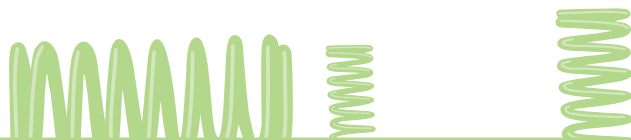
- Estimates of the direct rebound effect are contingent upon good data sets and would benefit from more robust methodologies. This is particularly case for quasi-experimental studies of household heating, where current evaluation practice is poor.
- Econometric studies need to address the potential sources of bias indicated in Section 3. There is scope for both econometric and quasi-experimental studies of a greater range of consumer energy services, provided that individual appliances can be monitored. However, the policy issue here is not so much changes in short-term utilisation patterns, but changes in the number and capacity of conversion devices over the longer term.
- Estimates of the direct rebound effect for personal automotive transport would benefit from more appropriate definitions of useful work. A study employing tonne kilometres as the dependent variable appears feasible and could potentially capture the effect of increasing car sizes. Analysis is also needed of other modes of transport, including freight.
- There is scope for more empirical work on the 'rebound effect with respect to time', especially in the area of transportation. More work is also

required on the dependence of direct rebound effects on income.

- The geographical bias of the evidence base also needs to be addressed. In particular, the evidence for rebound effects in developing countries is very weak.

2. Quantitative estimates of indirect and economy-wide rebound effects are feasible and should be pursued

- A combination of input-output analysis and life-cycle analysis can be used to estimate the embodied energy associated with various types of energy efficiency improvement. These estimates need to be developed more systematically and the results incorporated within technology and policy appraisals.
- Embodied energy analysis can also be combined with econometric models of consumer or producer behaviour to estimate the secondary effects from energy efficiency improvements by households. This approach is limited to rather aggregate categories of energy service and has a number of methodological weaknesses. Nevertheless, there is considerable scope for further research.
- Given the widespread use of CGE models in energy research, the lack of application to rebound effects is surprising. There is much scope for expanding the evidence base in terms of the countries and sectors studied and the different types of energy efficiency improvement that are modelled. However, the empirical basis for CGE models needs to be



improved and there is a need for more systematic and informed sensitivity analysis to highlight the importance of specific assumptions. This would help establish how robust the results are, and with what confidence they can be expressed.

- More robust estimates of economy-wide rebound effects may potentially be obtained from macro-econometric models. There is scope for further application of this methodology, in which some of the weaknesses identified here could be addressed.

3. Our understanding of the contribution of energy to economic growth needs to be greatly improved

- The linkage between economic measures of energy efficiency at the macro-level and physical/thermodynamic measures of energy efficiency at the micro level is poorly understood. While decomposition analysis is routinely used to identify the relative contribution of structural change and changes in various measures of energy efficiency, the relative importance of technical change, substitution between energy and other inputs, and changes in fuel mix remains unclear. Since standard assumptions about 'autonomous energy efficiency improvements' (AEEI) appear inconsistent with the available evidence, the projections of many energy-economic models may be misleading.
- Since thirty years of research has failed to reach a consensus on the

issue of substitutability between energy and capital, the underlying theoretical assumptions and/or methodological approach may be flawed. Future work should ensure that restrictions such as neutral technical change are tested for rather than assumed and only accepted on empirical grounds. Future studies should also use a flexible form for the production function, allow for non-neutral technical change, test the assumption of 'separability' between different inputs and pay closer attention to changes in product mix. A full meta-analysis of existing studies would also be beneficial, to further clarify the reasons for the differing results.

- Future research should investigate whether, how and to what extent different types of energy efficiency improvement at different levels of aggregation are associated with improvements in the productivity of other inputs and with improvements in total factor productivity.
- 'Ecological' models of economic growth challenge conventional assumptions and offer a promising route for further research. At present, this approach is largely ignored by mainstream economists, who generally pay insufficient attention to the contribution of energy to economic growth. While Saunders has used neoclassical growth theory to explore the rebound effect, the issue has not been addressed by contemporary research on endogenous growth theory and induced technical change. While

communication is inhibited in part by competing 'world-views', there should be scope for mutual learning and improved testing.

6.3 Policy implications

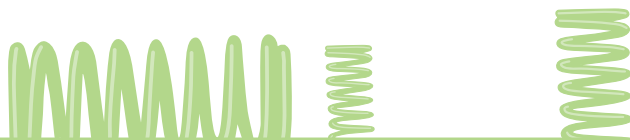
The general conclusion of this assessment is that rebound effects need be taken more seriously by analysts and policymakers than has hitherto been the case. While the effectiveness of energy efficiency policies has not been investigated, some general policy implications can nevertheless be drawn:

1. The potential contribution of energy efficiency policies needs to be reappraised.

- Energy efficiency may be encouraged through policies that raise energy prices, such as carbon taxes, or through non-price policies such as building regulations. Both should continue to play an important role in energy and climate policy. However, many official and independent appraisals of such policies have overstated the potential contribution of non-price policies to reducing energy consumption and carbon emissions.
- It would be wrong to assume that, in the absence of evidence, rebound effects are so small that they can be disregarded. Under some circumstances (e.g. energy efficient technologies that significantly improve the productivity of energy intensive industries) economy-wide

rebound effects may exceed 50% and could potentially increase energy consumption in the long-term. In other circumstances (e.g. energy efficiency improvements in consumer electronic goods) economy-wide rebound effects are likely to be smaller. But in no circumstances are they likely to be zero.

- Taking rebound effects into account will reduce the apparent effectiveness of energy efficiency policies. However, many energy efficiency opportunities are highly cost-effective and will remain so even when rebound effects are allowed for. Provided market and organisational failures can be overcome, the encouragement of these opportunities should increase real income and contribute to economic growth. They may not, however, reduce energy consumption and carbon emissions by as much as previously assumed.
- #### 2. Rebound effects should be taken into account when developing and targeting energy efficiency policy
- Rebound effects vary widely between different technologies, sectors and income groups. While these differences cannot be quantified with much confidence, there should be scope for including estimated effects within policy appraisals and using these estimates to target policies more effectively. Where rebound effects are expected to be large, there may be a greater need for policies that increase energy prices.



- 'Win-win' opportunities that reduce capital and labour costs as well as energy costs may be associated with large rebound effects. Hence, the implications of encouraging these opportunities need to be clearly understood and quantified. It may make more sense to focus policy on 'dedicated' energy efficient technologies, leaving the realisation of wider benefits to the market

3. Rebound effects may be mitigated through carbon/energy pricing – whether implemented through taxation or an emissions trading scheme

- Carbon/energy pricing can reduce direct and indirect rebound effects by ensuring that the cost of energy services remains relatively constant

while energy efficiency improves. Carbon/energy pricing needs to increase over time at a rate sufficient to accommodate both income growth and rebound effects, simply to prevent carbon emissions from increasing. It needs to increase more rapidly if emissions are to be reduced.

- Carbon/energy pricing may be insufficient on its own, since it will not overcome the numerous barriers to the innovation and diffusion of low carbon technologies and could have adverse impacts on income distribution and competitiveness. Similarly, policies to address market barriers may be insufficient, since rebound effects could offset much of the energy savings. A policy mix is required.



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Annex 1: Project team, expert group and contributors

Project Team

The assessment was managed by Steve Sorrell of the Sussex Energy Group, SPRU, University of Sussex. The contributors were as follows:

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Expert Group

The expert group was chosen for its combination of expertise on energy efficiency, energy economics and the rebound effect. It met twice during the course of the project, providing input to the initial framing of the issues, literature search, synthesis and drafting. The members were as follows:

Jim Skea (UKERC);

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Annex 2: Technical and Supplementary Reports

The results of the full assessment are contained in five in-depth Technical Reports, as follows:

Technical Report 1: Evidence from evaluation studies

(Matt Sommerville, Steve Sorrell)

Technical Report 2: Evidence from econometric studies

(Steve Sorrell, John Dimitropoulos)

Technical Report 3: Evidence from elasticity of substitution studies

(David Broadstock, Lester Hunt, Steve Sorrell)

Technical Report 4: Evidence from CGE modeling studies

(Grant Allan, Michelle Gilmartin, Peter McGregor, Kim Swales, Karen Turner)

Technical Report 5: Evidence from energy, productivity and economic growth studies

(Steve Sorrell, John Dimitropoulos)

In addition, there is a shorter Supplementary Note by Steve Sorrell on the graphical analysis of rebound effects. All these reports are available to download from the UKERC website.



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