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Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency

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ABSTRACT

Beginning with William Stanley Jevons in 1865, a number of authors have claimed that economically justified energy-efficiency improvements will increase rather than reduce energy consumption. 'Jevons Paradox' is extremely difficult to test empirically, but could have profound implications for energy and climate policy. This paper summarises and critiques the arguments and evidence that have been cited in support of Jevons' Paradox, focusing in particular on the work of Len Brookes and Harry Saunders. It identifies some empirical and theoretical weaknesses in these arguments, highlights the questions they raise for economic orthodoxy and points to some interesting parallels between these arguments and those used by the 'biophysical' school of ecological economics. While the evidence in favour of 'Jevons Paradox' is far from conclusive, it does suggest that economy-wide rebound effects are larger than is conventionally assumed and that energy plays a more important role in driving productivity improvements and economic growth than is conventionally assumed.

1. Introduction

The view that economically justified energy-efficiency improvements will increase rather than reduce energy consumption was first put forward by the British economist, William Stanley Jevons in 1865 (Jevons, 1865). If it were true, 'Jevons Paradox' would have profound implications for sustainability. It would imply that encouraging energy efficiency as a means of reducing carbon emissions would not just be futile but positively counterproductive. The conventional assumptions of energy analysts, policymakers, business and lay people alike would be turned on their head, the costs of adjusting to climate change will be significantly greater than expected and the dominant strategies for achieving sustainability would be undermined. This would be all the more the case if, as seems logical, the Paradox applied to resource efficiency more generally, rather than just energy efficiency. But is the Paradox logically coherent? Do the arguments in its favour stand up to close scrutiny? What empirical evidence is available to suggest that it is correct?

A widely cited formulation of Jevons Paradox is as follows 'with fixed real energy prices, energy-efficiency gains will increase energy consumption above what it would be without these gains' (Saunders, 1992b). Harry Saunders termed this formulation the 'Khazzoom–Brookes postulate', after two contemporary economists (Len Brookes and Daniel Khazzoom) who have been closely associated with the idea. The choice of the term 'postulate' is revealing, since it indicates a starting assumption from which other statements are logically derived and which does not have to be either self-evident or supported by empirical evidence. This interpretation both reflects and encourages a debate that tends to be polarised, theoretical and inconclusive. This paper seeks to move beyond this by treating the above statement as a hypothesis and exploring some testable implications.

The paper summarises and critiques the arguments and evidence that have been cited in support of Jevons' Paradox, focusing in particular on the work of Len Brookes and Harry Saunders. This work forms part of a broader literature on 'rebound effects' from energy efficiency improvements, which is reviewed by Sorrell (2007) and briefly introduced below.[1] However, the arguments cited in support of Jevons' Paradox generally do not include quantitative estimates of rebound effects. Instead, this work comprises a mix of theoretical argument, illustrative examples and 'suggestive' evidence from econometric analysis and economic history. It is these 'indirect' sources of evidence that are reviewed in this paper, together with a number of others that are not cited by the above authors but which appear relevant to

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[1] A previous and comprehensive review of rebound effects was provided by Greening et al. (2000). This was published in an special edition of Energy Policy devoted to rebound effects and edited by Schipper (2000), which provides an invaluable reference source.

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their arguments. While most of these sources of evidence make no reference to Jevons' Paradox they could arguably be used in support of the Paradox as well as challenging conventional wisdom in a number of areas. However, in all cases the evidence is suggestive rather than definitive.

The paper begins with an introduction to rebound effects, followed by a historical overview of the debate on Jevons' Paradox, including the 19th century example of energy-efficiency improvements in steam engines, together with more contemporary examples of 'general-purpose technologies'. This introduces the central theme of this paper: namely that the arguments and evidence used in support of Jevons' Paradox are closely linked to broader questions regarding the contribution of energy to productivity improvements and economic growth.

Section 2 summarises Brookes' arguments in favour of Jevons' Paradox, identifies some empirical and theoretical weaknesses and examines whether more recent research supports his claims. Section 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 methodologies. Section 4 examines some relevant evidence on the contribution of energy to productivity improvements and economic growth and points to the interesting parallels between Brookes' arguments and those of contemporary ecological economists. While the evidence remains ambiguous, the central argument is that energy—and by implication improved energy efficiency—plays a significantly more important role in economic growth than is assumed within mainstream economics. Section 5 highlights some of the implications of this finding for the economy-wide rebound effect. Section 6 concludes.

2. Rebound effects

The 'rebound effect' is an umbrella term for a variety of mechanisms that reduce the potential energy savings from improved energy efficiency. An example of a rebound effect would be the driver who replaces a car with a fuel-efficient model, only to take advantage of its cheaper running costs to drive further and more often.

The nature, operation and importance of rebound effects are the focus of a long-running debate within energy economics (Greening et al., 2000). 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. Simple 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. This increased consumption of energy services may be expected to offset some or all of the predicted reduction in energy consumption.

This so-called *direct rebound effect* was first brought to the attention of energy economists by Khazzoom (1980) and has since been the focus of much research (Greening et al., 2000). But even if there is no direct rebound effect 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, summarised in Box 1. Both direct and indirect rebound effects apply equally to energy-efficiency improvements by consumers and producers (Figs. 1 and 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 percentage of the *expected* energy savings from an energy-efficiency improvement. Hence, an economy-wide rebound effect of twenty per cent mean that twenty per cent of the potential energy savings are 'taken back' through one or more of the mechanisms indicated above. An economy-wide rebound effect of 100% means that the expected energy savings are entirely offset, leading to zero net savings for the economy as a whole. *Backfire* means that the rebound effects exceed 100%, leading to an overall increase in energy consumption—as Jevons predicted.

Rebound effects need to be defined in relation to particular *time frame* (e.g. short, medium or long term) and *system boundary* for the relevant energy consumption (e.g. household, firm, sector, national economy). For example, energy savings may be expected to be smaller for the economy as a whole than for the individual household or firm that is implementing an energy-efficiency improvement. The economy-wide effect is normally defined in relation to a national economy, but if energy-efficiency improvements lead to changes in trade patterns and international energy prices there may also be effects in other countries. Rebound effects may also be expected to increase in importance over time as markets, technology and behaviour adjusts. From the

Box 1–Indirect rebound effects.

Embodied energy 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.

Re-spending effects: Consumers may use the cost savings from energy-efficiency improvements to purchase other goods and services which themselves require energy to provide. As an extreme example, the cost savings from a more energy-efficient central heating system may be put towards an overseas holiday, leading to an increase in kerosene consumption.

Output effects: Producers may use the cost savings from energy-efficiency improvements to increase output, thereby increasing consumption of capital, labour and materials 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. All such improvements increase the overall productivity of the economy, thereby encouraging economic growth, increased consumption of goods and services and increased energy consumption.

Energy market effects: 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.

Composition effects: Both the energy-efficiency improvements and the associated reductions in energy prices will reduce the cost 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.

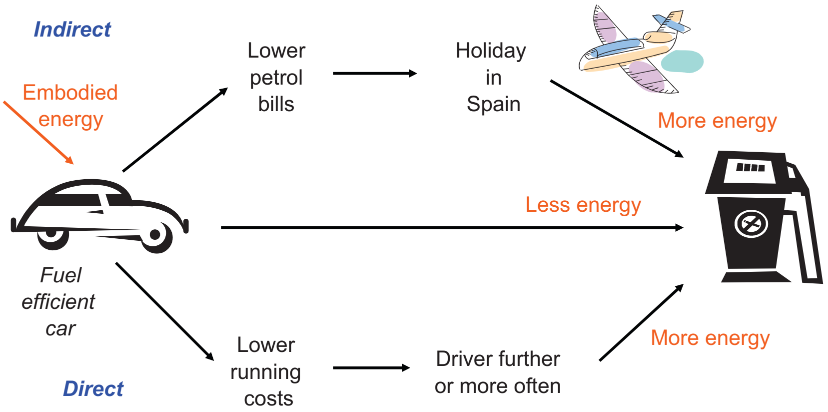

Fig. 1. Illustration of rebound effects for consumers.

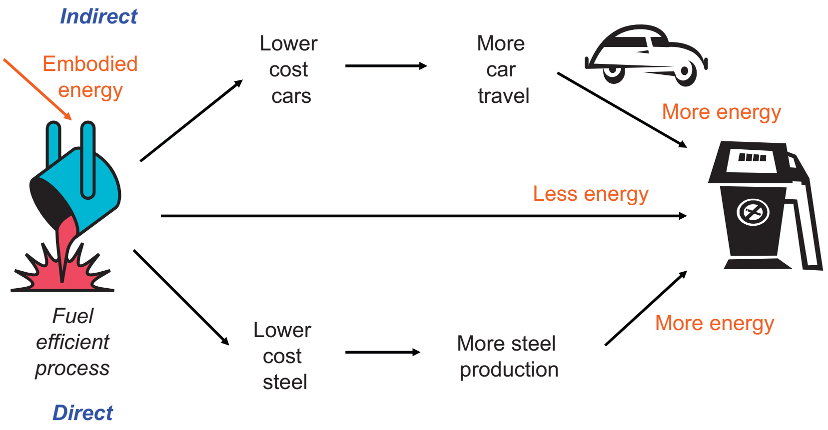

Fig. 2. Illustration of rebound effects for producers.

perspective of climate change mitigation, what matters is the long-term effect on global energy consumption.

3. Historical perspectives

Jevons first developed his ideas with reference to coal use and steam engines. His central claim is that:

> …it is 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)

He 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 (Fig. 3). 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 changes, including: '…contrivances, such as the crank, the governor, and the minor mechanism of an engine, necessary for regulating, transmitting, or modifying its power' (Alcott, 2005; Jevons, 1865). These developments were essential to the increased use of steam engines as a source of motive power and demonstrate how energy-efficiency improvements are frequently linked to broader improvements in technology and overall, or 'total factor' productivity.[2]

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[2] The economic productivity (or efficiency) of a 'factor' input such as energy is given by the ratio of output to input for that factor. Total factor productivity (TFP) is normally defined as the rate of growth of economic output minus the weighted sum of the rate of growth of inputs—with each input being weighted by its share in the value of output (Sorrell and Dimitropoulos, 2007). Unlike changes in individual factor productivity, improvement in total factor productivity are always desirable, since they indicate that more output is being obtained from the same quantity of inputs. Standard 'growth accounting' techniques estimate total factor productivity as the residual growth in output that is not explained by the growth of inputs. Such improvements are frequently attributed to 'technical change'.

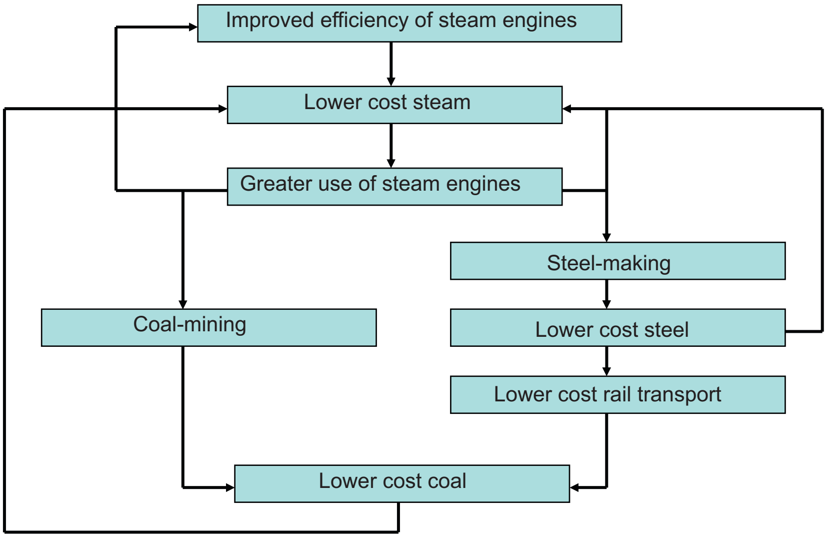

Fig. 3. Energy efficiency, positive feedbacks and economic growth.

Box 2–Defining 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 (Patterson, 1996). The options include:

Thermodynamic measures: where the outputs are defined in terms of either heat content or the capacity to perform useful work;

Physical measures: where the outputs are defined in physical terms, such as vehicle kilometres or tonnes of steel; or

Economic measures: where the outputs (and sometimes also the inputs) are defined in economic terms, such as value-added or GDP.

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'. The choice of measures for inputs and outputs, the appropriate system boundaries and the timeframe under consideration can vary widely from one study to another. However, physical and economic measures of energy efficiency tend to be influenced by a greater range of variables than thermodynamic measures, as do measures appropriate to wider system boundaries. Hence, the indicator that is furthest from a thermodynamic measure of energy efficiency is the ratio of GDP to total primary energy consumption within a national economy.

Economists are primarily interested in energy-efficiency improvements 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 overall, or 'total factor' productivity ('technical change'), and those that are not ('substitution'). The latter is assumed to be induced by changes in the price of energy relative to other inputs. The consequences of technical change are of particular interest, since this contributes to the growth in economic output. However, distinguishing empirically between these two categories can be challenging, not least because changes in relative prices also induce technical change.

Rosenberg (1989) has cited the comparable example of the Bessemer process for steel-making:

> [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 energy efficiency of production processes are deeply entwined with broader developments in process and product technology. While improved thermodynamic efficiency may form part of-or even a precondition for-such innovations, it does not follow that all the subsequent increase in energy consumption can be attributed to that efficiency improvement. More generally, it is possible to measure energy efficiency in a variety of ways for a variety of system boundaries (Box 2) and there is no consensus on the most appropriate definition for the purpose of estimating rebound effects.

The above examples relate to energy-efficiency improvements in the early stages of development of energy-intensive process technologies, producing goods that have the potential for widespread use in multiple applications. It is possible that the same consequences may not follow for energy-efficiency improvements in mature and/or non-energy-intensive process technologies, producing goods that have a relatively narrow range of applications. Similarly, the same consequences may not follow from

Table 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).

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.

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 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 per lumen hour. This, in turn, derived from continuing improvements in the energy efficiency of lighting technology, in combination with 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 1800–2000.

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 one thousand, 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 from the own-price elasticity of lighting services over this period. But this would be a questionable exercise over such a time interval, given the co-evolution and interdependence of the relevant variables. 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.

4. Energy and economic growth

Time-series data such as that presented in Table 1 are difficult to obtain, which partly explains why relatively little research has investigated the causal links between improvements in various measures of energy efficiency and more aggregate measures of economic output and energy consumption. While many studies demonstrate strong correlations between economic output and energy consumption, the extent to which the growth in economic output can be considered a *cause* of the increased energy consumption, or vice versa, remains unclear. It seems likely that there is a synergistic relationship between the two, with each causing the other as part of a positive feedback mechanism (Ayres and Warr, 2002b). Hence, to explore Jevons Paradox further, it seems necessary to investigate the nature, mechanisms and determinants of economic growth–a notoriously difficult topic.

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 (Barro and Sala-I-Martin, 1995; Denison, 1962; Gullickson and Harper, 1987; Jones, 2001). Economic growth is assumed to result instead from the combination of increased capital and labour inputs, changes in the quality of those inputs (e.g. better educated workers) and increases in total factor productivity that are frequently referred to as 'technical change'.

This view has been contested by ecological economists, who argue instead that the increased availability of 'high quality' energy inputs has been the primary driver of economic growth over the last two centuries (Beaudreau, 1998, 2005; Cleveland et al., 1984; Hall et al., 1986; Kummel et al., 2000, 1985). These authors emphasise that energy carriers differ both in their capacity to perform useful work (captured by the thermodynamic concept of 'exergy') and in their relative economic productivity—reflected by differences in price per kW h (Kaufmann, 1994). So for example, electricity represents a 'higher quality' form of energy than coal. 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 (Cleveland et al., 2000; Hong, 1983; Zarnikau, 1999).

Cleveland et al. (1984) claim that a strong link exists between *quality adjusted* energy use and economic output and this link will continue to exist, both temporally and cross-sectionally. This contrasts with the conventional wisdom that energy consumption has been 'decoupled' from economic growth. They also claim that a large component of increased labour productivity over the past 70 years has resulted from empowering workers with increasing quantities of energy, both directly and indirectly as embodied in capital equipment and technology (Cleveland et al., 1984). This contrasts with the conventional wisdom that productivity improvements have resulted from technical change. Other ecological economists argue that the productivity of energy inputs is substantially greater than the share of energy in total costs (Ayres, 2001; Ayres and Warr, 2005b)—again in contradiction to the conventional wisdom.

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, 2005b). More useful work can be obtained with the same, or less, energy consumption through improved thermodynamic efficiency. Hence, if increases in energy inputs contribute disproportionately to total factor productivity improvements and economic growth, then improvements in thermodynamic efficiency may do the same. Conversely, if increases in energy inputs contribute little to productivity improvements and economic growth, then neither should improvements in thermodynamic efficiency.

5. The contribution of Len Brookes

Despite their far-reaching implications, Jevons' ideas were neglected until comparatively recently and contemporary advocates of energy efficiency are frequently unaware of them. While the paper of Khazzoom (1980) stimulated much research and debate on direct rebound effects (Besen and Johnson, 1982; Einhorn, 1982; Greene, 1992; Greening et al., 2000; Henly et al., 1987, 1988; Lovins, 1988), most researchers ignored the long-term, macroeconomic 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 Jevons' Paradox and combined these with critiques of government energy efficiency policy (Brookes 1990a, b, 2004, 1978, 1984, 2000). Brookes' work has prompted a fierce response from critics (Grubb, 1990, 1992; Herring and Elliot, 1990; Toke, 1990), to which Brookes has provided a number of robust responses (Brookes, 1992, 1993).

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 (Sorrell, 2007).

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 appears to be an insufficient basis for claiming that backfire is inevitable.

Brookes also criticises the assumption that the demand for useful work will remain fixed while its marginal cost falls under the influence of raised energy efficiency, and the related assumption that individual energy savings can be added together to produce an 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 Jevons' Paradox suggests.

Brookes marshals a number of other arguments in support of Jevons' Paradox that appear more amenable to empirical test. In doing so, he highlights some important issues regarding the relationship between energy consumption, economic productivity 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*. Brookes cites two separate, but related sources of empirical evidence in support of this argument. The primary source is the work of Sam Schurr and colleagues on the historical importance of changes in energy quality (notably electrification) in driving US productivity growth (Box 3). The second, more indirect source of evidence is the work of Dale Jorgenson and others on the historical direction of technical change. Contrary to standard assumptions, Jorgenson's results suggest that, at the level of individual sectors, technical change has been 'energy-using', meaning that it has increased energy intensity over time rather than reduced it.[3] This work is also cited as suggestive evidence for Jevons' Paradox by Saunders (1992b).
- *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 appears to rest in part on the assumption that the per-capita 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 per-capita energy consumption in which different energy types are weighted by their relative economic productivities (Adams and Miovic, 1968).
- *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 to estimate what consumption 'would have been' in the absence of those improvements (Geller et al., 2006). The energy savings

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[3] Jorgenson and Fraumeni (1981) used econometric techniques to investigate the impact of the energy price rises of the 1970s on US manufacturing productivity. They employed the conventional neoclassical distinction between price-induced substitution between factor inputs and autonomous (i.e. non-price induced) technical change. They estimated the rate of change in the share of energy costs in the value of output of US manufacturing sectors (holding input prices constant) and found that, in 29 out of 35 sectors, the share of energy costs increased over time. This is termed 'energy-using' technical change. Generally, we would expect energy using technical change to be associated with 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 an increase in the price of energy will lower total factor productivity.

Box 3–Sam Schurr and the rebound effect.

Schurr (1982, 1983, 1984, 1985) and colleagues (Schurr et al., 1960) explored trends in US energy consumption, energy productivity and total factor productivity throughout the 20th century. Energy productivity was defined as the ratio of GDP to total primary energy consumption, with energy being measured on the basis of heat content. Over the period 1920–1953, energy, labour and total factor productivity were all found to be growing, while during the period 1953–1969, energy productivity was relatively unchanged while total factor productivity continued to grow rapidly. Both periods exhibited falling energy prices relative to other inputs and large increases in energy consumption, and were characterised by a decreasing share of coal in final energy consumption and an increasing share of oil and electricity. Also, in both periods, total factor productivity grew significantly faster than energy productivity.

Structural change in the economy and improvements in thermodynamic efficiency provided only a partial explanation of these trends. Since energy prices were falling in relative terms, energy substituted for other factors of production, thereby reducing energy productivity and improving capital and labour productivity. But these substitution effects were more than outweighed by technological improvements, facilitated by the availability of high-quality energy sources, which greatly improved the overall productive efficiency of the US economy. This meant that economic output increased much faster than energy consumption, owing to the greater productivity of capital and labour. The net result was to produce *falling* energy intensity (as measured by the energy/GDP ratio) alongside *rising* total energy consumption—as Jevons' Paradox predicts.

Schurr argued that the technological improvements which drove output growth depended crucially upon the increased availability of more 'flexible' forms of energy (oil and electricity) at relatively low costs. These contributed to changes in industrial processes, consumer products and methods of industrial organisation that were quite revolutionary—for example, in transforming the sequence, layout and efficiency of industrial production (Schurr, 1982). Schurr's pioneering contribution, therefore, was to highlight the importance of energy quality for productivity growth.

Brookes' uses these observations to support his case for backfire. His argument appears to be that (a) most improvements in energy productivity are associated with proportionally greater improvements in total factor productivity; (b) improvements in total factor productivity increase economic output, leading to a corresponding increase in demand for inputs; and (c) the resulting increase in demand for energy inputs more than offsets the reduced demand for energy per unit of output. Hence, energy consumption increases while aggregate energy intensity falls.

Box 4–Endogeneity and the rebound effect.

Trends in aggregate quantities may be expressed as the product of a number of variables. For example, economy-wide energy consumption (E) may be expressed into the product of population (P), GDP per capita ($A = Y/P$) and energy use per unit of GDP ($T = E/Y$): $E = PAT$. Decomposition analysis allows the change in energy use over a particular period to be estimated as the sum of the change in each of the right-hand side variables. The 'energy saved' by energy-efficiency improvements over a particular period can then be estimated by comparing current energy consumption with an estimate of what energy consumption 'would have been' had energy intensity (T) remained unchanged. For example, the IEA analysed data from 11 OECD countries over the period 1973–1998 to suggest that energy use would have been 50% higher in 1998 if end-use intensity had remained at its 1973 level (Geller et al., 2006). (*Note*: Strictly, this argument applies only to the use of Laspeyres indices in decomposition analysis, and not to competing approaches such as Divisia indices (Ang, 1999)).

But this approach is only valid if right-hand side variables are independent of one another—or at least if any dependence is sufficiently small that it can be neglected. In contrast, Brookes argues that improved energy efficiency enables both higher affluence ($A = f(T)$) and higher population ($P = f(T)$): ''... it is inconceivable that populations of today could be maintained with the technology of 500 years ago... inanimate energy allied to man's ingenuity is what has permitted the very large increase in output in the last 200 years without which the increase in population would not have occurred. Would this increase (and the associated increase in energy consumption) have occurred if conversion efficiencies had stayed at the abysmally low levels prevailing in the early years of the nineteenth century?'' (Brookes, 2000)

To capture this interdependence, the relationship could be better expressed as a system of simultaneous equations (Alcott, 2006):

$$E = f(P, A, T; X_E)$$
$$P = g(E, A, T; X_P)$$
$$A = h(E, P, T; X_A)$$
$$T = i(E, P, A; X_T)$$

Hence, while a reduction in the economy-wide energy/GDP ratio (T) may have a direct effect on energy consumption through the first of these equations, it may also encourage economic growth (A), which in turn will increase the total demand for energy (E). Over the long term, rising affluence may encourage higher population levels (P), which in turn will increase energy consumption (E). Each of these changes may in turn influence the energy/GDP ratio (T). Hence, a change in one variable is likely to trigger a complex set of adjustments and the final change in energy consumption could be greater or less than the direct change. Under these conditions, decomposition analysis could overestimate (or underestimate) the energy savings from improved energy efficiency.

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 of a counterfactual in this way is misconceived. This argument is not developed in detail by Brookes, but does raise questions over the use of 'decomposition analysis' to explore the rebound effect (Box 4).

Sorrell and Dimitropoulos (2007) describe the historical research that forms the basis for these arguments, summarise how Brookes uses this research to support his case and examine in detail whether more recent research confirms or contradicts Brookes' claims. They highlight a number of potential weaknesses, including the following:

- Schurr's work applies primarily to the causal effect of shifts to higher quality energy carriers (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, since the link between energy productivity and total factor productivity appears to vary greatly, both over time and between different countries and sectors.
- Neither Jorgenson and colleagues or comparable econometric 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 2000; Sanstad et al., 2006; Welsch and Ochsen, 2005). 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 change varies between sectors and types of capital as well as over time (Sue Wing, 2008; Sue Wing and Eckaus, 2007). Moreover, even if energy-using technical change were to be consistently found, the relationship between this finding and Jevons' Paradox remains unclear.[4]
- The 'accommodation' argument has its origins in 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 appears to rest in part on the assumption that the per-capita income elasticity of 'useful' energy demand declines asymtopically to unity as income increases, thereby allowing economic output to be represented as a linear function of useful energy inputs. While an earlier study by Brookes (1972) provides some support for this hypothesis, this has not been tested by more recent studies of income elasticity of energy demand since these typically measure energy consumption on the basis of heat content (Richmond and Kaufmann, 2006a, b; Stern, 2004b).
- 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.

In sum, each of these sources of evidence has empirical and theoretical weaknesses and the extent to which they (individually and collectively) support Jevons' Paradox 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 Jevons' Paradox.

Perhaps the most important insight from Brookes' work is that improvements in energy productivity are frequently associated with proportionally greater improvements in overall or 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 (Pye and McKane, 1998; Sorrell et al., 2004; Worrell et al., 2003). Such examples are frequently used by authors such as Lovins (1997) to support the business case for energy efficiency. But 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.[5] Much the same applies to the contribution of improved energy efficiency to overall productivity improvements and economic growth. But this leaves open the question of whether energy-efficiency improvements (however defined) 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.

6. The contribution of Harry Saunders

Harry Saunders has shown how Jevons' Paradox is broadly supported by neoclassical production and growth theory. His work is theoretical and is necessarily based on highly restrictive assumptions. But Saunders does not claim that his work *proves* Jevons' Paradox; instead, it simply provides suggestive evidence in its favour, given certain *standard* assumptions about how the economy operates.

Saunders (1992a, b) uses neoclassical growth theory to argue that backfire is a likely outcome of 'pure' energy-efficiency improvements-that is, a form of technical change (see Box 2) that improves energy productivity while not affecting the productivity of other inputs. In other words, this result does not rely on the contribution of energy to raising capital and labour productivity that is emphasised by Brookes. Neoclassical growth theory also predicts that 'pure' improvements in capital, labour or materials productivity will increase overall energy consumption. Since technical change typically improves the productivity of several inputs simultaneously, these models suggest that most forms of technical change will increase overall energy consumption compared to a scenario in which such improvements are not made.

Saunders' use of the neoclassical growth model was 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 (2000) subsequently demonstrated that backfire is still predicted by neoclassical theory when an alternative choice is made for the production function used to provide energy services. In a more recent contribution, Saunders (2008) focuses on the potential of different types of production function to generate backfire. Unlike Saunders

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[4] The relevance of this work to the rebound effect is not made clear by either Brookes or Saunders. The primary implication is that technical change has frequently reduced energy efficiency and thereby increased overall energy consumption, even while other factors (such as structural change) have acted to decrease energy consumption. Not only is this the opposite to what is conventionally assumed in energy-economic models, is also opposite to what is required for an empirical estimate of the rebound effect. At the same time, technical change has clearly improved the thermodynamic conversion efficiency of individual devices, such as motors and boilers. What Jorgenson and Fraumeni's work suggests, therefore, is these improvements in thermodynamic efficiency have not necessarily translated into improvements in more aggregate measures of energy intensity at the level of industrial sectors. Similarly, a more recent study by Sue Wing and Eckaus (2007) suggests that this has not necessarily translated into improvements in more aggregate measures of energy intensity for particular types of capital (e.g. machinery). In other words, improvements in energy efficiency at one level of aggregation may have contributed to greater energy consumption at a higher level of aggregation. Hence, the relevance of these results may hinge in part upon the appropriate choice of independent variable for the rebound effect.

[5] This also implies that so-called 'win-win' technologies may be associated with the largest rebound effects. For example, 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 twenty-five times greater than energy costs, the resulting cost savings can dwarf those from reduced energy consumption. But if the total cost savings are twenty-five times greater, the indirect rebound effects may be twenty-five times greater as well.

(1992a, b), 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).

Saunders (2008) 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 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.[6] 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, 2008).[7]

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 (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.[8] 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' 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 some extent, but to date no authors have used such models to explore the rebound effect. However, since what are at issue are 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.

7. 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 underlying theme in much of Brookes' work: namely that energy plays a more important role in driving productivity improvements and economic growth than is conventionally assumed. But precisely the same claim is made by ecological economists such as Cleveland et al. (1984), who attribute a large component of the productivity increases 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 Jevons' Paradox 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 shifts towards 'high-quality' fuels than to technological improvements in energy efficiency (Box 5). 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, 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

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[6] 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 (1992a, b) shows that the $KL)E$ form permits a range of values for the rebound effect (depending upon the Hicks elasticity of substitution between energy and the capital/labour nest), 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 (Broadstock et al., 2007; Frondel and Schmidt, 2004)

[7] 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). Saunders (2008) finds that imposing a global concavity restricition means that the Translog production function always leads to backfire. 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 all 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—but only if it can be empirically verified that concavity is honoured across the domain of measurement.

[8] Since Saunders (2008) demonstrated that Translog production functions are likely to lead to backfire, the validity of the earlier numerical simulations in Saunders (2005) must be questioned.

Box 5–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 kW h 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 aggregate 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 (*Note*: 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.), 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 constitutes a significant portion of the energy saved directly through energy efficiency improvements in each of those sectors.

Table 2
Trends in second-law conversion efficiencies of primary conversion processes in the US (average percentage 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).

between energy consumption and GDP (Chontanawat et al., 2006; Lee, 2006; Lee and Chang, 2005; Stern, 1993; Yoo, 2005; Zachariadis, 2006). The assumption is that if GDP growth is the cause of increased energy consumption then a change in the GDP 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 (Richmond and Kaufmann, 2006b; Stern, 2004a; Stern and Cleveland, 2004). 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 may have led earlier studies to draw misleading conclusions regarding the extent to which energy consumption has been decoupled from GDP (Kaufmann, 2004).

Finally, ecological economists have developed a number of alternatives to the conventional models of economic growth (Ayres, 1998; Ayres and Warr, 2002a; Ayres and van den Bergh, 2005; Ayres and Warr, 2005a, 2006; Beaudreau, 1995a, b, 1998; Beaudreau, 2005; Kummel, 1982, 1989; Kummel et al., 2002, 2000, 1985). 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.[9] The marginal productivity of energy inputs is found to be around ten times larger than their cost share, implying that improvements in energy productivity 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 (2005a), who combine historical data on the 'exergy' content of fuel inputs and second-law thermodynamic conversion efficiencies to develop a unique time series of the exergy output of conversion devices (termed useful work) in the US economy over the past century (Table 2). 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. By including useful work in their production function, rather than primary energy, Ayres and Warr (2005a, b) 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.

The implication of this work 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 some of Brookes' arguments in favour of backfire. However, the empirical evidence in support of this perspective remains patchy. 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 understood and conventional notions of causality may be problematic for systems as complex as modern economies (as Fig. 3 indicates). In a similar manner, the different variants of 'ecological growth models' rely upon an unusual and oddly behaved production function,[10] provide results that are difficult to reconcile with each other[11] and appear vulnerable to bias from a number of sources that could potentially invalidate the results[12] (Sorrell and Dimitropoulos, 2007). As a result, claims that the marginal productivity of energy is an order of magnitude larger than its cost share, or that improvements in thermodynamic conversion efficiencies can act as a suitable proxy for technical change, must be treated with considerable caution.

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

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 has provided a necessary condition for most historical improvements in economic productivity. 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).

The account of Schurr (1983, 1984, 1985) for the impact of electricity (and especially electric motors) on the organisation and productivity of US manufacturing provides an example of this process. But the extent to which such patterns have applied in other sectors and time periods needs to be determined empirically. If such a situation is the norm, the increased availability of high-quality energy may be 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 conversion efficiency may do the same, because both increase the useful work available from conversion devices. Under these conditions, the rebound effect could be large and potentially greater than unity.

8. Implications

Jevons' Paradox implies that *all* economically justified energy-efficiency improvements will increase energy consumption above where it would be without those improvements. Since this is a counterintuitive claim for many people, it requires strong supporting evidence if it is to gain widespread acceptance. The main conclusion from this paper is that such evidence does not yet exist. The theoretical and empirical evidence cited in favour of the Paradox contains a number of weaknesses and inconsistencies and most is only indirectly relevant to the rebound effect. 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 driving productivity improvements and 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; Laitner, 2000; Lovins, 1988, 1998; Schipper and Grubb,

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[9] 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.

[10] The so-called LINEX production function implies increasing marginal returns and variable marginal productivities.

[11] Ayres and Warr (2005a, b) claim that the inclusion of useful work rather than primary energy in the LINEX 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 using the same function but measuring energy inputs on the basis of heat content.

[12] The results suggest the presence of serial correlation and multicollinearity. Also, since the potential non-stationarity of the time series is not taken into account, the correlations could be spurious.

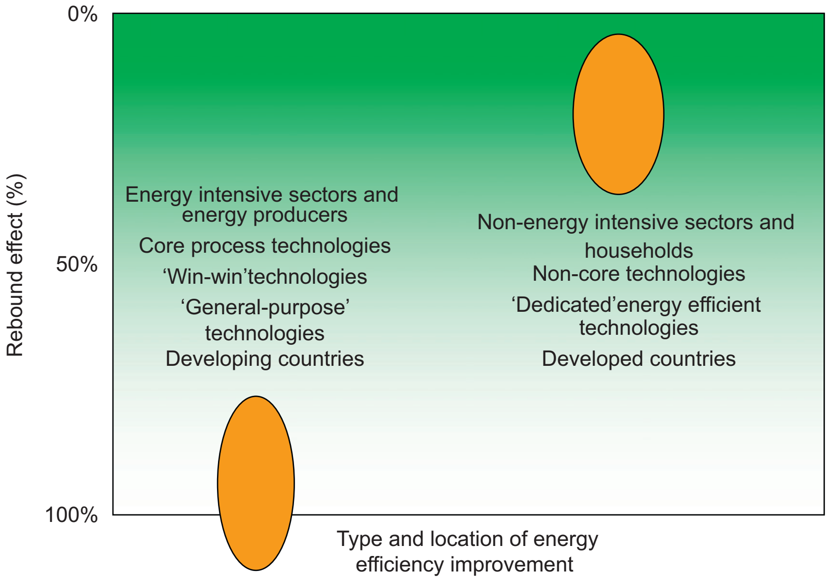

Fig. 4. Conditions under which rebound effects may be large or small.

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. This possibility is suggested by both Brooke's work and that of the ecological economists and is also demonstrated in a neo-classical framework by Saunders (1992a, 2005). 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 (Fig. 4).

Rebound effects may be particularly large for the energy-efficiency improvements associated with so-called 'general-purpose technologies', such as steam engines 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 nineteenth century, while electric motors provide a comparable illustration for the early 20th century. The former was used by Jevons to support the case for backfire, while the latter formed a key component of Schurr's work which was subsequently cited by Brookes as suggestive evidence for backfire.

The key to unpacking Jevons' Paradox may therefore be to distinguish the energy-efficiency improvements associated with GPTs from other forms of energy-efficiency improvement. Jevons' Paradox 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, Jevons' Paradox 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 climate policy should focus on encouraging dedicated energy-efficiency 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.

9. Summary

The case for Jevons' Paradox is not based upon empirical estimates of rebound effects. Instead, it relies largely upon theoretical arguments, backed up by empirical evidence that is both suggestive and indirect. Disputes over the Paradox, therefore, hinge in part on competing theoretical assumptions. While historical experience demonstrates that substantial improvements in energy efficiency have occurred alongside increases in economic output, total factor productivity and overall energy consumption, this does not provide sufficient evidence for Jevons' Paradox since the causal links between these trends remains unclear.

This paper has reviewed the strengths and weaknesses of the arguments and evidence in favour of backfire presented by Len Brookes and Harry Saunders. While neither author provides a totally convincing case in favour of Jevons' Paradox, their work poses an important challenge to conventional wisdom. Of particular interest is the apparent similarity between some of Brookes' arguments and the heterodox claim that the increased availability and quality of energy inputs is the primary driver economic activity. 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 could do the same, since both provide more useful work. The dispute over Jevons' Paradox may therefore be linked to a broader question of the contribution of energy to economic growth.

The debate over Jevons' Paradox would benefit from further distinctions between different types of energy-efficiency improvement. In particular, Jevons' Paradox 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 twentieth 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, the boundaries between them are blurred and GPTs account for a significant portion of total energy consumption.

Overall, while it is seems 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. This review suggests several possible avenues for research, which may supplement attempts to quantify rebound effects. First, econometric and decomposition techniques could be used to better understand the source of changes in aggregate energy efficiency (e.g. the relative contribution of structural change, technical change, input substitution, changes in fuel mix and other factors) (Sue Wing, 2008). Second, these techniques could also be used to investigate the extent to which different types of energy efficiency improvement are associated with improvements in the productivity of other inputs and with improvements in total factor productivity. Third, the implications of Saunder's work on neoclassical production theory could be further assessed, especially since the relevant functions underpin most standard energy-economic models. Finally, the ecological models of economic growth need more critical scrutiny, both to assess their statistical robustness and to explore whether and how they can be reconciled with more conventional approaches. While communication is inhibited in part by competing 'world-views', there should be scope for mutual learning and improved testing.

A prerequisite for all the above is a recognition that rebound effects matter and need to be taken seriously. Something is surely amiss when such in-depth and comprehensive studies as the Stern (2007) review overlook this topic altogether. While rebound effects are difficult to study, they are not necessarily any more difficult than well-researched issues such as price-induced technical change. Their continued neglect may result as much from their uncomfortable implications as from a lack of methodological tools. Too much is at stake for this to continue.

Acknowledgements

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