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ANALYSIS

Technological progress and sustainable development: what about the rebound effect?

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Abstract

Sustainability concepts that rest on the idea of resource- or energy-efficiency improvements due to technological progress tend to overestimate the potential saving effects because they frequently ignore the behavioral responses evoked by technological improvements. Efficiency improvements also affect the demand for resources and energy, and often an increase in efficiency by 1% will cause a reduction in resource use that is far below 1% or, sometimes, it can even cause an increase in resource use. This phenomenon is commonly labeled the rebound effect, which is well-known among energy economists, but never attracted much attention in ecological economics. The paper starts with the traditional neoclassical analysis of the rebound effect in a partial equilibrium framework that concentrates on the demand of one particular energy service such as mobility or room temperature. It also provides an overview of some of the main empirical studies based on this model that mostly confirm the existence of the rebound effect, but are controversial about its actual importance. However, we have to go beyond the neoclassical single-service model in order to take care of the variety of possible feedback affecting energy use. The paper presents two important expansions of the single-service model in order to show the potential relevance of the rebound effect to ecological economics. First, it is shown that in a multi-services model it proves to be difficult to make general statements about the relevance of the rebound effect. In this case, the overall effect of an increase in energy efficiency on total energy use depends on the on the assumptions about the substitutability between the services considered and the direction of the income effect. Second, the paper also tries to take care of the fact that changes in resource use or energy use are frequently just 'side-effects' of other forms of technological progress. Especially technological change of a time-saving nature can have a large influence on energy use as many time-saving devices (for example, faster modes of transport) require an increase in energy consumption that is frequently reinforced by a 'rebound effect with respect to time'. This effect will be especially strong when wages are high and, at the same time, energy prices are low, as is currently the case in most industrialized countries. Consequently, the paper also provides a strong argument for the introduction of energy taxes. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Many concepts of sustainable development emphasize the importance of efficiency improvements by technological progress. Technology is supposed to help us in promoting a society where it is possible to keep our present standard of life or even increase it while at the same time using less resources and especially less energy (see, for example, von Weizsäcker et al., 1997). These concepts rest on the idea that an increase in efficiency by 1% will, more or less, also lead to a decrease in resource use by 1%. However, this is usually not the case because technological improvements evoke behavioral responses. Often an increase in efficiency by 1% will cause a reduction in resource use that is far below 1% or, sometimes, it can even cause an increase in resource use. Among energy economists this phenomenon is known as the rebound effect[1], which, however has not been studied in detail by ecological economists.

The exact definition of the rebound effect varies in the literature. Sometimes, the term is used in a very general sense as a description of the functioning of market economies where increases in efficiency are frequently overcompensated by 'growth effects' (for example, Radermacher, 1997). An increase in the ratio of GDP to energy or to resource use does not necessarily lead to a decrease in energy or resource use because, at the same time, there will also be growth in economic activities. In this general sense the rebound effect describes increases in resource or energy efficiency that do not result in a corresponding decrease in energy or resource use. However, from this broad perspective, the growth in economic activities is not necessarily connected to efficiency improvements due to new technologies. The growth effects may be due to structural changes and a general growth tendency of market economies, which immediately leads into the discussion whether a continuously growing economy ever can be sustainable (Binswanger, 1995; Daly, 1996) and whether the growth tendency may be reversed. Although these are important topics, they will not be further elaborated in this paper as, here, we are interested in the more specific question how efficiency improvements due to technological progress affect the demand for resources and energy.

So far, the rebound effect has been mainly associated with energy use and the question how energy efficiency improvements affect energy consumption. Energy economists (especially Khazzoom, 1980, 1987; Brookes, 1990; Wirl, 1997) have come up with precise definitions of the rebound effect, which can easily be applied to resource use in general. This narrow but precise definition of the rebound effect is based on the following considerations. If technological progress makes equipment more energy efficient, less energy is needed to produce the same amount of product or service. However, the amount of product or service usually does not stay the same. Because the equipment becomes more energy efficient, the cost per unit of product or service that is produced with this equipment falls which, in turn, increases the demand for the product or the service. If energy efficiency of a car is increased by technological innovations, the 100 km can be driven with less fuel and, therefore, at lower cost. Consequently, people may drive more and longer distances because mobility (for example expressed in passenger km) has become cheaper.

Several empirical studies of the 1980s and 1990s confirm the existence of the narrowly defined rebound effect with respect to improvements of energy efficiency in heating systems and insulation as well as with respect to transport activities. Generally, economists seem to agree that there exists a rebound effect, but they disagree about its actual importance. The disagreement, to a large degree, is the result of the very strong assump-

[1] Most articles on the rebound effect can be found in the *Energy Journal* and *Energy Policy*. Recently, *Energy Policy* published a special issue (issue 6–7, vol. 28, 2000) on the rebound effect that provides an overview of the current state of the debate.

tions of the single-service model, from which the rebound effect is derived. It neglects the various possibilities of substitution effects among services as well as the income effect, and econometric studies based on the single-service model, therefore, can be misleading. In this paper we will argue that the rebound effect is indeed of empirical relevance and that behavioral responses evoked by efficiency increases can have a large impact on energy use even when we go beyond the single-service model in order to take care of the variety of the possible feedbacks affecting energy use.

The paper also tries to take care of the fact that changes in resource use or energy use are frequently just 'side-effects' of other forms of technological progress. Especially technological change of a time-saving nature can have a large influence on energy use as many time-saving devices (e.g. faster modes of transport) require an increase in energy consumption. An effect that, as will be shown, is reinforced by a frequently strong rebound effect, not with respect to energy but with respect to time, which adds a new perspective to the discussion of the rebound effect. This 'rebound effect with respect to time' will be especially strong when wages are high and, at the same time, energy prices are low, as is currently the case in most industrialized countries. High wages, which represent the opportunity costs of time, in combination with low energy prices encourage the increasing use of time-saving but energy-intensive devices leading to an overall increase in energy use as people constantly try to 'save' time.

The paper is organized as follows. Section 2 gives a precise definition of the rebound effect in a single-service model and also discusses the limits of this approach. Section 3 provides a summary of the main empirical studies which are largely based on the single-service model. In Section 4 we will outline the possible income and substitution effects that can be of considerable importance once we go from a single-service model to a multi-services model. Section 5 presents a further perspective on the rebound effect by considering time-saving innovations and their impact on energy use. Finally, Section 6 summarizes the main arguments.

2. The rebound effect for a single service in a neo-classical framework

This section presents the concept of the rebound effect that is commonly used by energy economists, but it also points out the potential shortcomings of this approach. A first systematic treatment of the rebound effect can be found in Khazzoom (1980), where it is described for a single-service model with a given preference structure (utility function). The model focuses on households' demand for energy services such as mobility (measured in passenger km) or room temperature rather than on the demand for energy per se, which, in turn, is derived from the service demand. The relation between energy use and service demand is captured by the energy efficiency μ, which is defined as the ratio between service output s and the energy input e that is required to produce s

$$\mu = \frac{s}{e} \tag{1}$$

For example, if s stands for passenger km, μ denotes the number of passenger km driven/l of fuel consumption. Consequently, the service s may also be expressed as the product of the technical efficiency and energy consumption. One may drive a km in an energy-efficient car (high μ) with low consumption of fuel or in a car with low energy efficiency (low μ) with high consumption of fuel.

The use of more efficient equipment raises the demand of s because it lowers the costs of s. As is common in neoclassical economics, the marginal cost of producing the service is supposed to equal its price. Therefore, we may express the marginal costs (or the price), P, of s as

$$P = p_e/\mu \tag{2}$$

where p_e stands for the price of energy. Condition (2) allows us to calculate the price elasticity of the demand for service s, which we denote $\eta_P(s)$

$$\eta_P(s) = \frac{\mathrm{d}s}{\mathrm{d}P}\frac{P}{s} = \frac{\delta(\mu e)}{\delta\left(\frac{p_e}{\mu}\right)}\frac{\frac{p_e}{\mu}}{\mu e} = \frac{\delta e}{\delta p_e}\frac{p_e}{e} = \eta_{p_e}(e) \tag{3}$$

and which equals the (energy) price elasticity of energy $\eta_{p_e}(e)$.

The elasticity of energy demand with respect to efficiency $\eta_\mu(e)$ can then be expressed in terms of the price elasticity of the demand for service s, $\eta_P(s)$

$$\eta_\mu(e) = \frac{\delta e}{\delta \mu}\frac{\mu}{e} = \frac{\delta\left(\frac{s}{\mu}\right)}{\delta \mu}\frac{\mu}{e} = \left[\frac{\delta s}{\delta \mu}\frac{1}{\mu} - \frac{s}{\mu^2}\right]\frac{\mu}{e}$$

$$= \frac{\delta s}{\delta \mu}\frac{\mu}{s} - 1 = \frac{\delta s}{\delta\left(\frac{p_e}{P}\right)}\frac{\frac{p_e}{P}}{s} - 1 = \frac{\delta s}{\delta\left(\frac{1}{P}\right)}\frac{\frac{1}{P}}{s} - 1$$

$$= -\eta_P(s) - 1 \qquad (4)$$

which is the expression that can also be found in Khazzoom (1980). The elasticity of energy demand with respect to efficiency is, same as the elasticity with respect to energy price, determined by the price elasticity of service demand and equals to -1 minus the price elasticity of service demand. Eq. (4) implies that a 1% increase in energy efficiency leads to a decrease in energy demand by $(1 - |\eta_P(s)|)$%.

Eq. (4) defines the rebound effect in an exact way. It is the percentage of the technical energy conservation potential that is offset by an increase in the service demand. As long as $\eta_P(s) > -1$, the rebound effect is less than 100%. Otherwise, the rebound effect could even cause an increase in energy demand if efficiency is increased. However, empirical results suggest that the demand for energy services is usually rather inelastic and, therefore $-1 < \eta_P(s) < 0$ (see, for example, Greening and Greene, 1997).

Although the single-service model presented in this section gives a precise definition of the rebound effect, we have to be aware of the fact that it is based on a number of restrictive assumptions that deserve special attention:

- The model only includes one single service from which consumers derive utility. Implicitly a single-service model assumes separability of a single service s from all other services, which is a reasonable assumption only as long as substitution between different services (substitution effect) and the income effect are of a negligible quantity. In reality, however, these effects may be quite important and the rebound effect derived from a single-service model may under- or overestimate the actual feedback, which also depends on the substitution effects and the income effect that will take place.[2] In Section 4 we will expand the single-service model and we will take a look at the influence of substitution and income effects.
- Only energy was explicitly considered as an input to the production of the service s. However, other inputs may also be relevant for the production of energy services, such as capital goods and ‘time’ (e.g. the time necessary for driving a certain distance). In many cases, possible substitution effects between the inputs will also affect energy use. As will be shown in Section 5, it is especially time-saving technological progress that frequently exerts a large influence on energy use. In this case, changes in energy use are only a ‘side effect’ of households’ time-saving efforts.
- Implicitly the model assumes reversibility of investment in energy saving devices. Households would, therefore, constantly adjust their capital stock to new optimal levels whenever capital and energy prices change. However, a large part of investment in energy-saving devices seems to be of an irreversible nature. Once an energy saving device is introduced it is usually used for quite a long time no matter

[2] Greening and Greene (1997) have proposed a terminology where they distinguish between three different types of rebound effects. First, there is the increased use of an energy service induced by the reduction in its price due to greater efficiency, which represents the direct rebound effect. Second, holding the prices of other commodities constant, the reduction in the cost of an energy service implies that the consumer has also more money to spend on all other goods and services as there is also an income effect. Other goods and services also require energy, and so total energy use will increase in areas not directly affected by the energy efficiency improvement, which Greening and Greene call the indirect rebound effect. Third, changes in the prices of firms’ outputs and changes in the demand for inputs caused by income and substitution effects will propagate throughout the economy and result in adjustments of supply and demand in all sectors, resulting in general equilibrium effects. By taking care of the income effect, we also include the indirect rebound effect in our analysis, but we still neglect general equilibrium effects.

how prices will change (see Walker and Wirl, 1993). Therefore, the model probably overestimates the flexibility of households and, in reality, they will react less to price changes than suggested by the model.

In Sections 4 and 5 we try to show how the relaxation of the first two of these assumptions makes the rebound effect a more complex phenomenon than suggested by the single-service model. However, as we will argue, the rebound effect remains an empirically relevant phenomenon also under conditions that are closer to reality.

3. Empirical studies based on the single-service model

The original paper by Khazzoom (1980) stimulated a series of empirical research on the rebound effect during the 1980s and 1990s. Especially during the 1980s the relevance of the rebound effect was a much debated issue because oil and gas prices were on a high level which stimulated a lot of investment in energy saving devices (Walker and Wirl, 1993). However, when oil and gas prices came down in 1986 the economic incentive to invest in energy saving devices declined again. Moreover, as energy prices did not change much since 1987 and, because many empirical studies on the rebound effect were based on regressions using time series of energy prices, few new insights could be gained from studies using more recent data.

Table 1 summarizes the result of some of the main empirical studies of the 1980s and 1990s which investigated either the effect on energy use of more efficient heating systems or weatherization, or tried to derive the size of the rebound effect in car use from regression models. Transport and dwelling are the two areas where improvements in energy efficiency are of empirical relevance. A study by Biesiot and Noorman (1999, p. 379), for example, tries to calculate the energy saving options of Dutch households due to better insulation and energy efficient dwelling, as well as due to improvements in energy efficiency in transport by which total energy use of households could be reduced by $\sim 30\%$.

In general, the empirical studies suggest that the rebound effect is indeed of empirical relevance, but its size varies considerably depending on data and method employed in the studies. Generally, the rebound effect seems to be somewhere between 5 and 50%[3] implying that energy saving technologies will still lead to a reduction in energy consumption, but that part of the saving potential is lost because of the induced increase in service demand.

However, most of these empirical studies can be criticized for various reasons. First, the rebound effect is frequently not directly observed, but derived from estimated price elasticities of service demand (especially the rebound effect in car use) which according to Eq. (4) also determine the size of the rebound effect in the single-service model. However, this model is based on a very restrictive ceteris paribus clause as outlined in Section 2. Second, energy-price elasticities are usually not constant and tend to be higher for periods of rising energy prices than for periods of falling energy prices (Haas and Schipper, 1998). Therefore, estimated price elasticities of samples covering periods of rising energy prices (the 1970s and early 1980s) may not be appropriate for deriving the size of the rebound effect during periods of falling energy prices (the late 1980s and early 1990s).

Consequently, these empirical studies cannot tell us the complete truth about the actual feedback between increases in energy efficiency and energy use. However, they suggest that improvements in energy efficiency related to transport as well as dwelling, indeed, will cause a feedback in energy use, although the exact size of the estimated rebound effects should be interpreted with caution.

[3] Based on their estimated energy-price elasticities, Haas and Schipper (1998) find the 'aggregate rebound effect' for total residential energy demand of households to be small in most of the countries they have studied.

Table 1
Empirical studies on the rebound effect

Study	Sample	Results
The impact of improved mileage on gasoline consumption (Blair et al., 1984)	Vehicle miles traveled in Florida (monthly data) from 1967 to 1976	RE-effect of 21%
An econometric model integrating conservation in the estimation of the residential demand for electricity (Khazzoom, 1986)	Study of electrically heated homes in Sacramento, CA	Long-run RE-effect of 65%
Price effect of energy efficient technologies (Dubin et al., 1986)	Study of 214 households participating in a program of improving the efficiency of home heating	RE-effect between 8 and 13%
An analysis of the impact of residential retrofit on indoor temperature choice (Dinan, 1987)	Study of a sample of 252 households whose dwellings were weatherized	RE-effect small but statistically significant
Changes in indoor temperatures after retrofit based on electricity billing and weather data (Hirst, 1987)	Study based on an evaluation of Residential Weatherization Program throughout the Pacific Northwest, which compared the behavior of the homes that participated in the program with nonparticipants	RE-effect between 5 and 25%
Forecasting a state-specific demand for highway fuels: the case for Hawaii (Leung and Vesenka, 1987)	Vehicle miles traveled in Hawaii (annual data) from 1967 to 1980	RE-effect of 25%
The effectiveness of mandatory fuel efficiency standards in reducing the demand for gasoline (Mayo and Mathis, 1988)	Vehicle miles traveled in the US (annual data) from 1958 to 1984	Short-run RE-effect of 22% and long-run RE-effect of 26%, however, statistically not significant
The FHWA/Faucett VMT forecasting model (Weinblatt, 1989)	Vehicle miles traveled in the US (annual data) from 1966 to 1985	RE-effect below 10%
The US demand for highway travel and motor fuel (Gately, 1990)	Vehicle miles traveled in the US (annual data) from 1966 to 1988	RE-effect of 9%
Vehicle use and fuel economy: how big is the 'rebound effect'? (Greene, 1992)	Vehicle miles traveled in the US (annual data) from 1966 to 1989	RE-effect between 5 and 19% depending on model
Another look at US passenger vehicle use and the rebound effect from improved fuel efficiency (Jones, 1993)	Vehicle miles traveled in the US (annual data) from 1966 to 1990	Short-run RE-effect of 13% and long run RE-effect of ~30%
Asymmetric energy demand due to endogenous efficiencies: an empirical investigation of the transport sector (Walker and Wirl, 1993)	Road transport in France, Germany and Italy from 1961 to 1985. The demand for transport services is derived from an annual technological fuel efficiency series (km/l of gasoline) that multiplied with the energy demand of a year yields the demand for transport services	Long-run RE-effects between 32 (Germany) and 51% (Italy)
Gasoline tax as a corrective tax: estimates for the US (Haughton and Sarker, 1996)	Vehicle miles traveled in 50 US States (annual data) from 1970 to 1991	Long-run RE-effect of 22%
Fuel economy rebound effect for US household vehicles (Greene et al., 1999)	Analysis of household survey data at 3-year intervals over a 15-year period in the US from 1979 to 1994	Long-run RE-effect of ~20%

4. Expanding the single-service model

During the 1980s, there was a heated debate in the *Energy Journal* about the actual significance of the rebound effect mainly between Lovins (1988), and Khazzoom (1987, 1989). Khazzoom, based on the results of his own and other empirical studies, argued that the rebound effect is empirically relevant and generally has a significant influence on energy use. Lovins, on the other hand, stated 'that rebound in demand [is]... not in general a significant one' with a theoretical maximum rebound probably on the order of 2% (Lovins, 1988, p. 155). However, most of Lovins's statements are not based on any empirical evidence as noted in Khazzoom (1989). Reevaluation of Lovins's arguments shows that, nevertheless, there remains one argument against the empirical validity of the rebound effect that could be of relevance as it refers to the limits of the single-service model. Lovins (1988, p. 158), claims that the rebound effect is more likely to be an income effect rather than a price effect, which would lead to a drastically lower response. In other words, the possible substitution effects between different services have to be considered along with the resulting income effect of energy-efficiency increases.

In a multi-services model, the overall effect of an increase in energy efficiency on energy consumption depends on the substitutability between different services and on the direction of the income effect. This may be illustrated graphically by a two services model. First, we consider two services with high substitutability and, second, we analyze the situation when there are two services with low substitutability, which is the case Lovins refers to in his paper. In this context the household's budget constraint can no longer be neglected as was the case in the single-service model. We assume that a typical household's utility $u(s_1, s_2)$ depends on two services, s_1 and s_2, and faces a budget constraint $B = p_1s_1 + p_2s_2$ where p_1 and p_2 are the prices of the two services.

In the first case, we assume that B is a household's fixed travel budget that can be used either for travelling by train (s_1) or by car (s_2) and that 1 km traveled by train needs less energy per person than 1 km traveled by car. To keep the model simple, we further assume that there is an exogenously given increase in fuel efficiency, which allows for travelling a mile by car with less fuel, however it is still less efficient than travelling by train. The effect of the increase in fuel efficiency is graphically shown in Fig. 1.

The resulting change in total fuel consumption depends on the size of the income and substitution effects. As shown in the single service case, the increase in fuel efficiency makes a service cheaper and increases the demand for the service. In our example, travelling by car becomes cheaper and travelling by car will partially be substituted for travelling by train. This is the substitution effect which in our case is supposed to be large as a household can usually easily substitute travelling by car for travelling by train. Additionally, there is also an income effect now, which was neglected in the single service case. The income effect is likely to lead to a further increase in passenger km traveled by car because the same travel budget B now allows for travelling more km than before. Both effects, income and substitution effect, tend to increase fuel demand in this example and the overall 'rebound effect' is even larger than suggested by the single-service model.

The second example describes the effect of an exogenously given increase in energy efficiency when there is low substitutability between the two services considered. To illustrate this case, we assume that B now describes a household's leisure budget, which can either be used for leisure activities that can be done without travelling by car (s_1) or for leisure activities that involve travelling by car (s_2). Consequently, s_1 needs less energy than s_2 if measured, for example, by the energy use per hour of leisure activity. This example is illustrated in Fig. 2.

If the substitutability of the two services is low, the substitution effect is of negligible magnitude. This assumption is valid if lower prices resulting from an increase in fuel efficiency will not induce households to shift to more transport intensive leisure activities. Furthermore, Lovins's arguments suggest that the income effect would primarily increase the demand for activities that do not involve additional car trips as travelling by

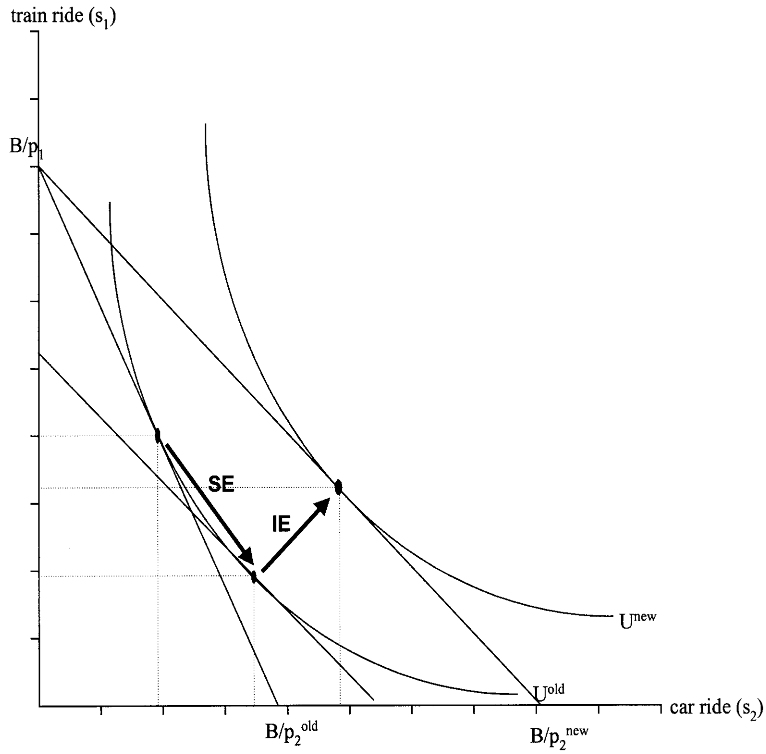

Fig. 1. Substitution and income effects when there is a high degree of substitutability between two services and when both services are normal goods.

car becomes an inferior good beyond a certain level of income. In this case, the rebound effect derived from the single-service model would be insignificant in reality because the income effect would work in favor of a reduction in energy use and the substitution effect would be very low.

Whether Lovins's claim is actually true depends on the question whether there exists a critical level of income where energy-intensive activities become inferior and whether the majority of households in developed countries is already beyond such a critical level of income. This question can hardly be answered in the affirmative, although direct empirical knowledge in this respect is scarce (see e.g. Biesiot and Noorman, 1999). Aggregate data on energy consumption of households in developed countries show no clear trends since the early 1970s. However, decomposition of the changes in energy use in different sectors in ten OECD countries over the period from 1973 to 1992 (Schipper et al., 1996, 1997) strongly suggests that the production of energy-intensive services still increases with households' income, which may be taken as evidence against Lovins's claim of the inferiority of energy-intensive services at the current level of income in most households.

Summing up, the two examples of a two-services model shown in this section illustrate the difficulty of making general statements about the relevance of the rebound effect. The overall effect of an increase in energy efficiency on total energy use depends on the services considered as well as on the assumptions about the substitutability between these services and the direction of the income effect. Consequently, the feedback in energy use may in fact become larger (Fig. 1) or smaller (Fig. 2) than suggested by the single-service model, depending on the services that are included in the model. Generally, the feedback will be smaller or even become negative if households spend additional income on services whose energy intensity is low. However, there is no convincing

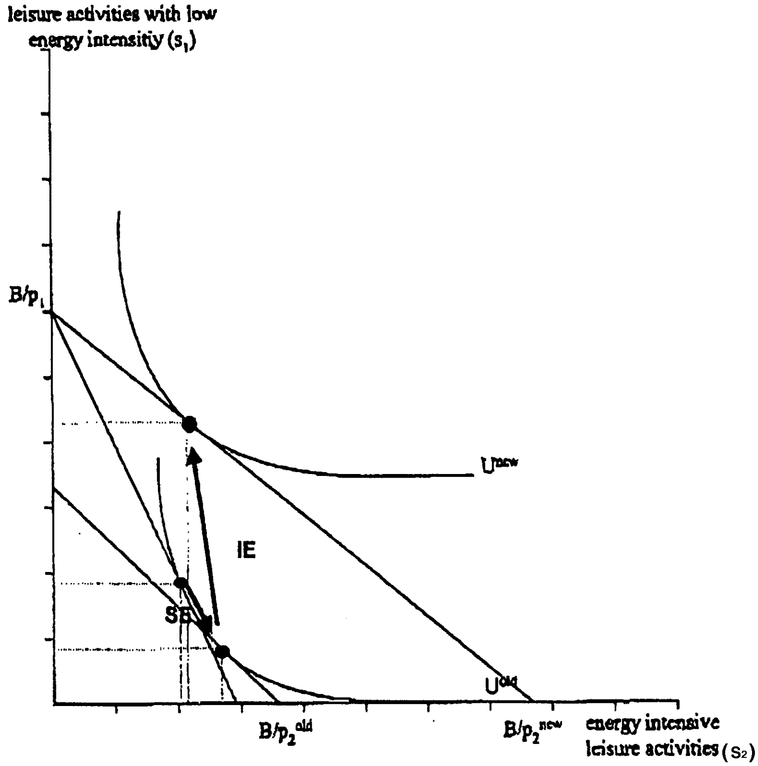

Fig. 2. Substitution and income effects when there is a low degree of substitutability between two services and when one service is inferior.

empirical evidence that would suggest the existence of such a trend.

5. Time-saving innovations: their impact on energy use and the importance of energy taxes

So far, the focus of the paper has been on improvements in energy efficiency of the production of energy services and their impact on total energy use. In the single-service model (Section 2) we considered energy as the only relevant input needed for the production of a service and, therefore, technological progress only mattered if it resulted in an increase in energy efficiency. However, many technical improvements are not implemented with the intention to change the energy efficiency of a service, but they still can have a large impact on energy use. This especially will be the case during times when energy prices are comparatively low as is the case for fossil fuels since 1986. During times of low energy prices the incentive to increase energy efficiency is low as energy costs are often a negligible part of a household's budget. For example, a recent empirical study on the evolution of energy efficiency of several household appliances (Newell et al., 1998) shows that increases in energy efficiency mainly occurred in times of comparatively high energy prices. Instead, households care much more about other aspects of technological progress.

One of the most important aspects of technological progress is the increase in efficiency of working time as well as consumption time, as was especially emphasized by Becker (1965)[4], that re-

[4] Becker (1965) uses the expression 'time productivity' instead of 'time efficiency' which, however, in this context means the same thing.

sulted in an increase in households' earnings but also in an increase in the efficiency of consumption time. The examples mentioned by Becker are supermarkets (saves shopping time), automobiles (saves time spent on transport), sleeping pills (saves 'unproductive' time spent in bed without sleeping), electric razors (saves time on shaving, which before was high because men used to go to the barbers' shop for this purpose) and telephones (saves time on visiting people's home). More recently, new developments regarding information technology and the internet may also be interpreted as time-saving innovations as they reduce the necessary time inputs for the production of many services. For example, e-commerce further increases the time efficiency of shopping, the use of e-mail reduces the time spent on writing and sending letters, and access to the internet reduces the time needed to gather information on many subjects.

However, the increase in the efficiency of consumption time (time-saving technological progress) often has a substantial impact on households' energy consumption because time-saving devices frequently require more energy. The speeding up of many processes requires additional energy as is most evident from transport where higher time efficiency (faster modes of transport) is usually associated with a larger input of energy. Automobiles need more energy than bicycles and airplanes need more energy than automobiles if measured by the energy used per passenger km[5]. Moreover, an increase in time efficiency may also lead to a 'rebound effect with respect to time'. Therefore, the impact on energy use can be quite large because we have to consider two effects. First, the introduction of time-saving devices increases the energy input necessary for the production of one unit of a service. Second, there is a 'rebound with respect to time', which is similar to the rebound effect with respect to energy described in Sections 2 and 4. This means that the introduction of a time-saving device used for the production of a service will also lead to an increase in the demand for the service.

The 'rebound with respect to time' often results in the paradoxical effect that households will not 'save' any time at all although they invest a lot in time-saving appliances (Linder, 1970). Consequently, if a service (for example, mobility) can be produced with less time, households will demand more of this service and substitute it for other services that are more time intensive (for example, cooking) and usually less energy intensive. In other words, people commute longer distances, but they eat in fast food restaurants in order to 'save' time. Therefore, the overall effect of time-saving technological progress will be an increase in energy use due to a larger demand for services that exhibit a high efficiency in consumption time while the time-saving potential may also be lost because of the larger demand for the service.

If there is an increase in the efficiency of consumption due to some time-saving innovations, it implies a decline in the time input required to produce a unit of a service. The decline reduces the costs associated with time, which is conventionally measured by foregone earnings. Consequently, substitution will be induced towards this service as its relative production costs in terms of foregone earnings will fall while production costs of other services whose production is time intensive will rise. This effect will be the stronger the higher earnings are and, therefore, foregone income from work. The secular increase in wages since World War II in all developed countries created a strong incentive to implement time-saving devices as the opportunity costs of time were constantly rising.

We may illustrate the impact of time-saving innovations on energy use by the following simple model, which builds on the household-production-function approach as developed by Becker (1965), Michael and Becker (1973).[6] A particular service s_i is supposed to be produced with the

[5] The more recent time-saving innovations concerning information technologies seem to be important exceptions from this general tendency because an increase in the speed of transmitting and handling information does not require larger energy inputs.

[6] Juster and Stafford (1991), Gronau (1997) provide surveys of more recent contributions in this field. As every model, the household-production-function approach also has its specific shortcomings especially with respect to the allocation of time (see, for example, Pollack and Wachter, 1975; Sharp, 1981; Gronau 1986).

inputs time, t_i, energy, e_i and a vector of market goods, x_i

$$s_i = f(t_i, e_i, x_i) \quad (5)$$

A household's utility function is

$$U = u(s_1, s_2, \ldots, s_n) \quad (6)$$

and depends solely on the services 'produced' within the household. It is further assumed that with respect to every service s_i, $u_i > 0$, $u_{ii} < 0$, where u_i (u_{ii}) denotes the first (second) derivative with respect to s_i. Work in the market does not involve any marginal utility or disutility and the value the household places on its time equals the fixed wage rate w.[7] Utility is maximized subject to the household production function constraints and a constraint on the household's available time T

$$T = t_w + \sum t_i \quad (7)$$

where t_w is the time spent in the labor market and t_i the time spent in producing service s_i. Furthermore, there is a budget constraint B, which in our model is

$$B = \sum (p_e e_i + p_i x_i) \quad (8)$$

where p_e is the market price for energy and p_i is the price of the market-good input used in producing s_i.

The time and budget constraints can be combined in a single resource constraint on the household's 'full income' S, a concept introduced by Becker (1965). The 'full income' S is the maximum money income achievable by a household if all time available would be spent working at the wage rate w.[8] If a household's nonwage income is zero, as we will assume in our model, the full income S is

$$S = wT = \sum (wt_i + p_e e_i + p_i x_i) \quad (9)$$

The utility function is, therefore, maximized subject to the constraints of the production functions (Eq. (5)) and full income (Eq. (9)). The Lagrangian can be expressed as

$$\text{Max}\, u(s_1, s_2, \ldots, s_n) - \lambda \sum [(wt_i + p_e e_i + p_i x_i) - S] \quad (10)$$

If we additionally rule out joint production (especially joint usage of time) the first order conditions with respect to two services s_j, s_k are (Michael and Becker, 1973)

$$u_j = \lambda\left(w\frac{\delta t_j}{\delta s_j} + p_e\frac{\delta e_j}{\delta s_j} + p_j\frac{\delta x_j}{\delta s_j}\right) \quad (11)$$

$$u_k = \lambda\left(w\frac{\delta t_k}{\delta s_k} + p_e\frac{\delta e_k}{\delta s_k} + p_k\frac{\delta x_k}{\delta s_k}\right) \quad (12)$$

and

$$\frac{u_j}{u_k} = \frac{w\dfrac{\delta t_j}{\delta s_j} + p_e\dfrac{\delta e_j}{\delta s_j} + p_j\dfrac{\delta x_j}{\delta s_j}}{w\dfrac{\delta t_k}{\delta s_k} + p_e\dfrac{\delta e_k}{\delta s_k} + p_k\dfrac{\delta x_k}{\delta s_k}} = \frac{\pi_j}{\pi_k} \quad (13)$$

The ratio of the marginal utilities of two services s_j and s_k equals the ratio of their marginal costs π_j and π_k, where the derivatives in Eq. (13) are the marginal input–output coefficients, which can be obtained by using the rule for differentiating inverse functions.

Assuming that all services are 'normal goods' we can already draw some general conclusions regarding the impact of time-saving innovations on a household's demand for a specific service and on its energy consumption. If, for example, there is a time-saving innovation concerning the production of the service s_j, this will result in a decline in $w\delta t_j/\delta s_j$ and hence, in a decline in the numerator of the right-hand side of Eq. (13) as less time is needed to produce an additional unit

[7] This is, of course, a simplification as actually one should distinguish between different ways of using time, which are not valued equally. However, the main thrust of the argument does not depend on the simplification as the value placed on time in non-work activities seems to correlate with the wage rate (see, for example, Button, 1993, pp. 52–58).

[8] As Becker (1965) explains, this does not imply that all time would be spent 'at' a job. Sleep, food and even leisure would be required for efficiency, and some time would have to be spent on these activities in order to maximize money income.

of s_j. And the effect will be the stronger the higher is the wage rate w. The decrease in the nominator of the right-hand-side of Eq. (13) will, in turn, cause a substitution of s_j for s_k, leading to a decline in the term on the left-hand side of Eq. (13) in order to restore equilibrium. In other words, due to the time-saving innovation, households will demand more of s_j as it becomes cheaper in terms of foregone income from work. If s_j stands for mobility and there is a time-saving innovation in transportation technology (faster cars or faster public transport), people will travel longer distances as a certain distance can be traveled at a lower opportunity cost. However, at the same time, time-saving innovations will cause an increase in energy as long as s_j is more energy intensive than s_k, and as long as p_e is small as compared to w, as is typical in developed countries.

The main application of the framework developed in this section is, of course, transport. There is quite a lot of evidence suggesting that time-saving innovations in transport lead to an increase in the demand for mobility as predicted by our analysis. One early hypothesis in this context is the fixed travel time budget hypothesis that states that households have a stable travel time budget (see Goodwin, 1978; Sharp, 1981, p. 99; Zahari et al., 1981). In other words, whenever there is a time-saving innovation that allows people to travel the same distance within less time, they will increase their mobility at an amount that exactly compensates for the time saved due to the innovation. The fixed travel time budget hypothesis, however, is not a commonly accepted hypothesis, but empirical evidence suggests that the total time allocation to travel even increases as the opportunity costs of time fall (time-saving innovations) or as income increases (Schipper, 1996), leading to an even larger increase in the demand for mobility than suggested by the fixed travel time budget hypothesis.[9]

[9] Of course, other factors such as structural changes in the economy may also have contributed to the increase in mobility and it is not solely due to the rebound effect with respect to time. Moreover, there are also large differences between countries and the average distance traveled in the US is much higher than in Europe or in Japan (Schipper, 1996, p. 121).

Finally, emphasizing the role of time-saving innovations provides an additional argument in favor of taxing energy, as for example suggested by the idea of an ecological tax reform, according to which the government should use the proceeds to finance part of the social security system (lowering indirect labor costs). As can be seen from Eq. (13) the substitution towards less time-intensive but more energy-intensive services caused by a time-saving innovation will be the stronger the higher the average wage rate w is in comparison to the energy price p_e. Consequently, the development of the relative prices of labor and energy in developed countries over the last decades, that led to an increase in wages relative to energy prices, strongly supported the induced substitution effects as it paid off to save time, but it did not pay off to save energy.[10] An ecological tax reform would be a an important measure to counteract the trend of constantly introducing more time-saving devices that at the same time are more energy intensive, and it would dampen the rebound effect with respect to energy as well as with respect to time.

6. Conclusion

Based on the arguments presented in this paper, the rebound effect with respect to households is indeed a relevant phenomenon that is too often neglected in the discussion of sustainable development. Sustainability concepts that rest on the idea of resource or energy improvements due to technological progress tend to overestimate the actual saving effects because they ignore the behavioral responses evoked by technological improvements that lead to the rebound effect. Of course, resource-saving technological change is a necessary condition for a decrease in resource intensity of economic activities. However, it is not a sufficient condition because of the rebound effect with respect to energy as well as, and probably even more important, the rebound effect with respect to time.

[10] In transport, this trend was also supported by the widening gap between land prices in cities and land prices in the country-side, which made people move out of the cities.

In the most simple case, one can analyze how an increase in energy efficiency in the production of a single service changes the demand for that service, provided that the only relevant input used for producing the service is energy. This rather strong assumption underlies the single-service model that traditionally has been used by energy economists and which is restated in Section 2

The single-service model provides an accurate description of the rebound effect as long as substitution between different services and the income effect are of negligible quantity. However, this assumption is not always valid, and, in this case, the estimated rebound effects based on the single-service models may under- or overestimate the actual feedback in energy use induced by higher energy efficiency. Especially Lovins (1988) argued along these lines by stating that the rebound effect was more likely to be an income effect rather than a price effect. Consequently, the single-service model would be misleading and one would have to consider the income and substitution effects between different services. In a multi-services model, as shown in Section 4, it is difficult to make general statements about the relevance of the rebound effect. The overall effect of an increase in energy efficiency on total energy use depends on the particular services considered as well as on the assumptions about the substitutability between these services and the direction of the income effect. But there is no evidence that would question the relevance of the rebound effect even in a multi-services model. On the contrary, the feedback will even be stronger than suggested by the single-service model if substitutability between services is high and if the demand for energy services increases with income (positive income effect).

However, the traditional single-service model of the rebound effect may also prove to be too restrictive in another respect as it concentrates on energy as the only relevant input in the production of a service. Especially time is a further important input to the household production of services and time-saving innovations can exert a large influence on energy use of households. Therefore, the paper offers a further perspective on the rebound effect (Section 5), where the focus is on time-saving innovations. Time-saving devices usually require more energy as is most evident from transport where an increase in the efficiency of time use (faster modes of transport) tends to be associated with a larger input of energy. If there is a time-saving innovation in the production of a particular service (for example, mobility), it can be produced with less time and at the same time households will demand more of this service (a rebound effect with respect to time) and substitute it for other services that are more time intensive but usually less energy intensive. Therefore, the overall effect of time-saving technological progress will be an increase in energy use.

All perspectives on the rebound effect presented in the paper support the claim that resource-saving or energy-saving technological progress will not be sufficient in order to make the economy sustainable because of the induced feedback in energy or resource demand. But the traditionally used single-service model of the rebound effect does not capture the full range of these feedbacks. Moreover, energy use is also strongly influenced by innovations of a time-saving nature. The higher are the opportunity costs of time (wage rate) and the lower are energy prices, the more these innovations tend to increase the overall energy use. Therefore, an ecological tax reform that would increase the relative price of energy in comparison to the wage rate would be an important step to actually reduce energy consumption in the household sector as it dampens the ‘rebound effect with respect to energy’ (as described in Sections 2 and 4) as well as the ‘rebound effect with respect to time’ as long as time-saving devices are energy intensive.

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