Wuppertal Institute
for Climate, Environment
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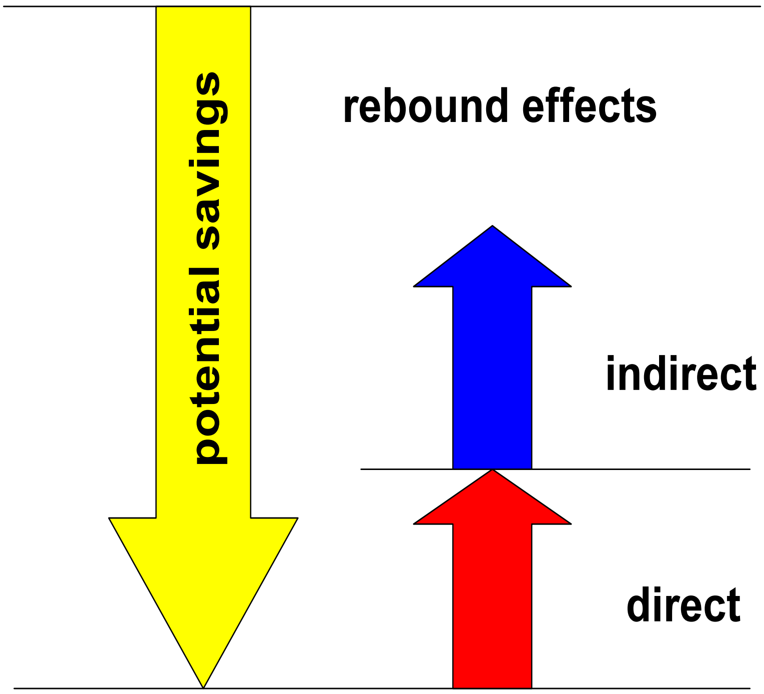
Ronald Schettkat

Analyzing Rebound Effects



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Abstract

Are efficiency improvements in the use of natural resources the key for sustainable development, are they the solution to environmental problems, or will second round effects — so-called rebound effects — compensate or even overcompensate potential savings, will they fire back? The answer to this question will have fundamental policy implications but the research on rebound effects does not provide clear results. This paper aims to clarify the theoretical basis of various analytical approaches which lead to widely different estimates of rebound effects.

JEL-classification: O13 — Agriculture; Natural Resources; Energy; Environment; Other Primary Products, O33 — Technological Change: Choices and Consequences; Q01 — Sustainable Development; Q3 — Nonrenewable Resources and Conservation, Q30 — General, Q31 — Demand and Supply; Q4 — Energy Q40 — General, Q41 — Demand and Supply; Q5 — Environmental Economics, Q50 — General, Q55 — Technological Innovation

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1 Introduction

Improvements in resource efficiency[1] are important for sustainable development but only if second round effects, i.e. economic responses to higher resource productivity — so called rebound effects — are not compensating or even overcompensating the potential savings of resources thus made possible. Are efficiency improvements in the use of natural resources the key for a sustainable development, are they the solution to environmental problems, or will rebound effects compensate or even overcompensate potential savings, will they fire back? The attractiveness of efficiency improvements, of technological solutions to environmental problems is obvious since they allow continuing with "business as usual" avoiding other measures which may be perceived as welfare reductions. But if rebound effects are very high, efficiency strategies cannot contribute substantially to sustainable development but may — as some authors argue — be the cause of environmental problems rather than the solution.

Generally "rebound effects" are defined as non realized savings in the use of resources relative to potential savings, where the latter are often set proportional to the efficiency gains. Setting potential efficiency gains proportional to actual efficiency gains abstracts from complex reactions to efficiency gains and in the literature is often labeled as "engineering effect". Actually, efficiency gains may reduce prices and raise demand for a specific resource (so called **direct effects**, through substitution and/or income/output effects). Even if no direct demand response occurs, rising real income resulting from price reductions for products in satiated markets may cause a growth of demand elsewhere in the economy (so called **indirect effects**) and therefore may cause higher demand for the resource. The complexity of these second round effects, the theoretical approach, and the level of abstraction may "explain" the diversity of estimated rebound effects ranging from a few percentages to 100% or more (Jevons' paradox, Khazzoom-Brookes postulate), but the existence of rebound effects is undisputed in the literature.

The analysis of rebound effects is challenging because it touches almost all relations in the economy ranging from 'simple' demand reactions to price and income variations, via substitution effects in consumption and production, dynamic aspects of adjustment processes to the most fundamental issues, as the origins and development of our needs and wants. Although challenging to analyze, a deep understanding as

[1] Patterson (1996) mentions various meanings of energy efficiency, which are based on
1. Thermodynamic
2. Physical Thermodynamics (output measured in physical units (miles), hybrid indicator)
3. Economic-thermodynamic
4. economic (market values nominator and denominator)

well as reliable estimates of rebound effects are vital for conservation policies. The higher non-realized savings of natural resources — or of greenhouse gas emissions — are relative to potential savings, the less efficiency improvements can contribute to a sustainable economic development. However, if rebound effects are strong, sufficiency strategies will most likely fail as well. High rebound effects result from unsatisfied needs or new wants and if these are important, sufficiency strategies may lack support. The precondition for a success of sufficiency strategies, a sufficient level of consumption (private and public), is then simply not given.

However, strong rebound effects can also be countered by policy measures and their analysis may help to identify the most appropriate instruments. If the rebound effect is large, price measures become relatively more effective compared to standards because high energy prices can counteract the rebound effect. With low rebound effects standards may be more appropriate. These policies may interfere with price trends (many analyses of rebound effects actually assume declining prices) and/or setting norms, they may steer expenditures to less environmentally damaging products. Economic growth and conservation may go together or may even be mutual conditions as Nicholas Stern argues.[2] In a multi-commodity environment, total use of natural resources can increase or decrease with rising income depending on preferences (see Berkhout/Muskens/Velthuijsen 2000, and below).

In the following, the fundamentals of demand and price reactions are discussed leading to a summary of critical assumptions made explicitly or implicitly in analyses, which are investigated in the following sections.

[2] Nicholas Stern's talk at the conference celebrating Andrew Glyn's life and work in Oxford, September 27, 2008

2 Fundamentals of the rebound effect

2.1 Defining the rebound effect

“Rebound effects” are defined as non realized savings in the use of resources relative to potential savings in the use of these resources.

RE = 1 – SR/PR

Where: RE = rebound effect, SR = saved resources, PR = potentially saved resources

A major problem is the estimation of PR and here different approaches may be chosen. Potential savings may be set proportional to the improvements in resource efficiency (in the literature often labeled as the engineering approach, Berndt/Wood 1975) or they may be calculated as a base line scenario with which the actual development is then compared (as in some macro analyses). The engineering approach is static assuming no other changes than the efficiency improvement, whereas a base line scenario may be dynamic in the sense that other trends are taken into account (e.g., exogenous changes in industry structure, general economic growth[3]).

In general, efficiency gains and changes in effective costs of natural resources will cause some reaction of economic agents. These can be extremely complex and not directly observable (probably unobservable) and obviously some assumptions need to be made to model these reactions (see below). Reactions to efficiency gains may affect the use of a specific resource in which the efficiency gain occurred, directly (so called **direct effects**, either through substitution or income/output effects) or indirectly through growth processes i.e. rising demand for other goods and services initiated by the increase in real income (so called **indirect effects**).

[3] Assuming that economic growth is requiring higher resource input.

2.2 Efficiency gains vs. price reductions

Many analysts equate efficiency gains to price reductions. The rationale for this equation is that a more efficient resource is more useful (more productive) in consumption or production and therefore less expenditures are necessary to achieve a certain level of utility, respectively production. However, this may be an overly simplifying assumption for several reasons:

- the efficiency gain may not be costless (which would reduce the rebound effect)
- price reductions of a particular resource can be independent of the prices of other inputs but efficiency gains may affect several inputs simultaneously. In this case the substitution effect (and with it the rebound effect) may be overestimated
- price elasticties may be asymmetric, i.e. the reactions to price increases may be different from reactions to price reductions
- efficiency may be endogenous, i.e. high expected consumption may affect the choice of the technology (e.g., investment in insulation of buildings may be influenced by the size of the house)
- price trends may affect efficiency
- full costs of consumption may include opportunity costs (time costs)
- markets may be imperfect

Price elasticity and the rebound effect

Price elasticity of a final service (S) which actually provides utility:

$$\varepsilon_{S,Ps} = \frac{\Delta S / S}{\Delta Ps / Ps}$$

$\varepsilon_{S,Ps}$ = 0; no response to changes in prices (ΔPs)

$\varepsilon_{S,Ps} = -1$; proportional response to changes in price

$\varepsilon_{S,Ps}$ may be greater |-1| depending on the demand function (see text).

Efficiency elasticity of a natural resource (R):

$$\varepsilon_{R,E} = \frac{\Delta R / R}{\Delta E / E}$$

The elasticity of the use of the natural resource in response to efficiency gains of this resource (direct rebound effect) can be expressed as:

$$\varepsilon_{R,E} = -1 - \varepsilon_{S,Ps}$$

$\varepsilon_{R,E}$ = 0; i.e., no response of the use of the natural resource following the improvement in efficiency, i.e. $\varepsilon_{S,Ps}$ =-1 (proportional response of the use of the final service to the rising efficiency (falling real price))

$\varepsilon_{R,E}$ = -1; i.e. the use of the natural resource declines proportional to the improvements in efficiency, i.e. $\varepsilon_{S,Ps}$ = 0 (the use of the final service does not respond to changes in costs of the provision of this service).

2.3 Final services and natural resources

Demand for natural resources — whether used in consumption or production — is usually derived demand in the sense that it is actually only one among several other inputs in the production of final "services" (for a discussion of the production of "final services" see Lancaster 1991 and also Becker 1965). Lancaster developed a concept of services in which they are produced within households as a combination of goods and time. For example, consumers produce the final service "mobility' using a combination of a car, fuel and time. In the energy literature "useful work" is often used referring to a similar concept. The household production function is a useful concept here because it shows that not only goods but also time are used to produce final services. Both, goods (income) and time may constrain the consumption of final services. In the example of mobility, the price of fuel is just one component in the "production" of mobility and consumers will only react to the extent that improved fuel efficiency affects the costs of mobility (see also the elasticity formula). Furthermore, "fuel efficiency" may be substantially or entirely depending on the engine technology (see also below section 5).

Time (approximated by opportunity costs or income, see below) may constrain the rebound effect. But time constraints may also be relaxed by the use of time-saving devices, which may cause a so-called parallel rebound effect. Examples used are flights versus car or train rides, dish-washers versus conventional cleaning. However, a deep analysis of these issues would not only require income-expenditure but also time data, which seldom exists.

2.4 Analytical methods and data

Some analysts argued that the analysis of rebound effects is grounded in neoclassical economics, which is certainly true for these theoretical analyses which also predict substantial rebound effects (for a substantial discussion see

Berkhout/Muskens/Velthuijsen 2000). However, 'neoclassical' is sometimes used to describe an overly simplified analysis (e.g., M. Binswanger 2000 claims that his multi-service analysis goes beyond the neoclassical single-service model) but the single-service assumption seems not to be the core of neoclassical economics. It seems that the core assumptions of neoclassical economics rests on perfect markets (competition), full information, rational behavior (utility maximization), independent economic agents following their interest and who are only affected by other agents through markets (methodological individualism). Analyses which claim 'utility maximization' may be overly abstract or 'empty' because individuals are assumed to maximize and thus any behavior is interpreted as 'utility maximizing' as long as it is not specified how wants and needs are weighted.

All economists regard prices and income as important variables steering behavior but many — also many economists who classify themselves as neoclassical — will deviate from overly narrow assumptions. A large part of empirical work tries to "let the data speak" although it needs to make — explicit or implicit — assumptions.

Most important for empirical analysis seems whether actual market outcomes can be interpreted as equilibrium if adjustment is slow (Goodwin 1992). Deviations from equilibrium cause adjustments but with frictions in markets it may take long to achieve a new equilibrium and frictions may even drive an economy away from equilibrium (as the famous cob-web theorem illustrates). Adjustments require time and therefore short-run and long-run reactions to changes in prices may deviate. Plausibly, the variety of options available is larger in the long-run than in the short-run, which may cause short-run and long-run rebound effects to deviate. However, it is not a priori clear that long-run rebound effects are necessarily larger than short-run rebound effects.[4]

4 Some empirical studies claim long-run rebound effects to be much larger than short-run rebound effects but other studies do not find any differences.

The estimates of rebound effects will, of course, substantially depend on

- the level of analysis (micro, macro, household, overall economy)
- the time frame (short run, long run)
- the theoretical assumptions
- assumption about efficiency gains (exogenous, endogenous)
- the estimation technique

These issues will be discussed in the following sections.

2.5 Wants, needs, satiation

'More is always better than less': although each additional unit of a product presents less utility than the preceding units, satiation should never be reached. If 'utility' is applied in the very abstract sense this statement may hold, but wants and needs may be very specific — nutrition, shelter, mobility etc. — and clearly satiation occurs in specific markets. General satiation was often diagnosed but waves of new possibilities, of innovations pushed our consumption up and up. Nobody (even the industry experts did not) foresaw the electronic revolution which made computers an every-day tool and consumption good. Nobody foresaw the enormous mobility, the possibility of vacation for almost everybody in the industrialized world, nor the enormous distances we can travel these days. Therefore, a higher level of utility, more of something, may be valid at the very abstract level but certainly not with respect to specific goods.[5]

Why do we demand ever more? Two views may be identified: One regards our wants as exogenously given and never saturated, only the way we satisfy these wants changes and depends on prices (Stigler/ Becker 1977). Individuals are only connected through market interactions but otherwise independent (methodological individualism). The other view argues that wants are to a substantial part created by society, by non-market interaction between individuals. Examples for the latter are John Kenneth Galbraith (1958) or Robert Frank (1999), who emphasizes rising income inequality and elite consumption which is transmitted to the average household through mass media and substitutes the "Jones" as traditional reference group. Since the income distribution widened in the US, the excessive consumption of celebrities became the reference also for the average consumer. For sure, marketing and consumption of reference groups influences average standards of 'necessary consumption'. But Hollywood celebrities driving hybrid cars may shift consumption also to more environmentally conscious styles of living.

[5] Whether ever new products improve our wellbeing is another issue. Research on happiness suggests that up to a certain income level GDP growth substantially raises happiness but the relationship is pretty flat once a certain income has been reached (for an overview Layard 2006).

3 The rebound effect in consumption

3.1 Components of the direct rebound effect

Usually the relationship between the price of a product and the quantity demanded is assumed to be negative, i.e. with falling prices demand will rise (see Figure 3.1). If one interprets an efficiency gain as a price reduction — as many authors do — it follows that demand for the product will expand, by how much depends on its own price elasticity. Assuming prices fall proportionally to the efficiency gains, proportional demand expansions require a (hyperbolic) demand function with a constant elasticity of one, i.e. in this case the direct rebound effect will be 100%. In this case, efficiency gains will be compensated to a 100% by the direct rebound effect. As is known from models of monopolistic price-setting, the price elasticity of demand will decline along a linear demand function. I.e. with a linear demand function efficiency gains — always assuming they translate into proportional price reductions — result in more than proportional expansions in demand if the price elasticity of demand is greater than one[6] (at high prices and small quantities), i.e. the direct rebound effect will be more than 100% (so-called unsaturated market). At the other end, however, the price elasticity may be smaller than one (at low prices and high quantities), i.e. price reductions will lead to less than proportional expansions of demand and the direct rebound effect will be smaller than 100%, although not zero (so-called saturated market).

Lower prices for a product made possible by efficiency gains result c.p. in higher real income, which may be spent on that product or elsewhere. The direct rebound effect from rising income would result in an outward shift of the demand curve for that product, i.e. for a given price a higher quantity would be demanded. However, the income gain may also be spent elsewhere in the economy, which may then indirectly raise demand for the resource which experienced an efficiency gain (indirect rebound).

6 It is common to drop the sign of the price elasticity since it is generally assumed to be negative.

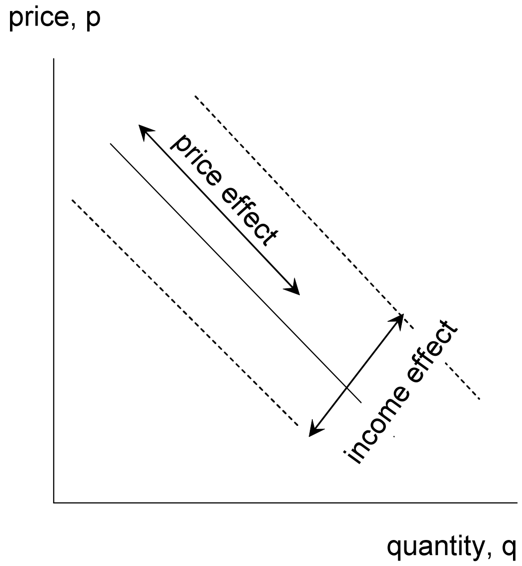

Figure 3.1: Income and price effects in price-quantity space

3.2 Efficiency gains and substitution

Assuming consumers have well ordered preferences and maximize utility, then the point where the budget constraint is tangential to a utility function (marked with U in Figure 3.2) is the optimal combination of the two goods. In Figure 3.2 the individual can either consume the natural resource or other goods (which may be a composite of other products). The maximum consumption of the natural resource is given by the budget divided by the price of the resource (point A in Figure 3.2). In the upper diagram q_R consumption of the natural resource and q_{OG} consumption of other goods are the utility maximizing position. An outward shift of the budget constraint would allow the individual to achieve a higher utility level (U2, instead of U1).[7]

Now let the efficiency of the natural resource increase, i.e. the budget would allow to buy more of the natural resource (a shift of the maximum consumption of the natural resource from A to A', see the middle diagram in Figure 3.2) or — in other words — the budget constraint turns in point B. Since the relative prices have changed in favor of the natural resource, the utility maximizing consumer would now consume q_R' and q_{OG}', i.e. the consumption of the natural resource in response to its increase in efficiency will be higher than before, which is the combined effect of substituting other goods by the natural resource and the higher income caused by the efficiency gain (so called uncompensated or Marshallian demand).

[7] It is usually assumed that the preference curves (U1-U1, U2-U2) are homothetic, i.e. the functions are assumed to be parallel to each other. Then an increase in income would shift the budget constraint, but would leave the relative consumption of the two goods unchanged.

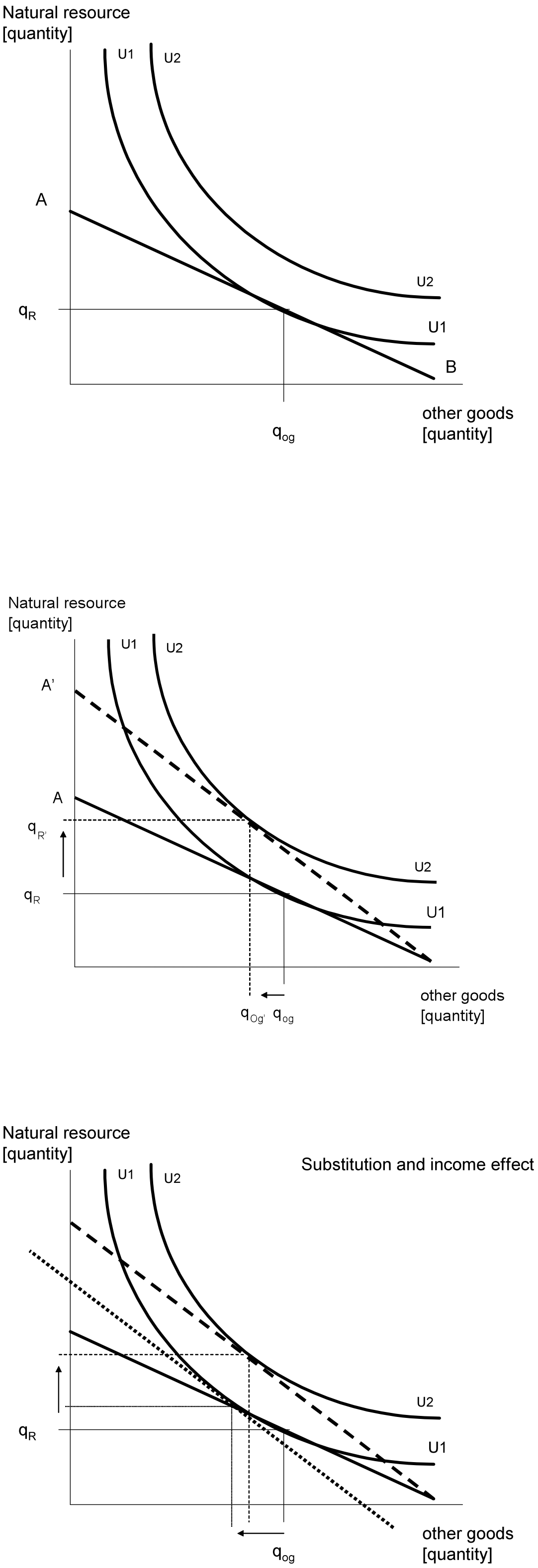

Figure 3.2: Consumption effects of efficiency gains

The lower diagram of Figure 3.2 shows the decomposition of the uncompensated (Marshallian) effect, into a substitution (compensated, Hicksian) effect and an income effect. The substitution effect is calculated holding income constant, i.e. it expresses the pure effect of a change in relative prices. Substitution and income effect together are equal to the overall effect. Clearly the shape of the indifference curves of preferences determines the effects. The utility function in Figure 3.2 is drawn in a way that more of a specific good is always better than less, but that the marginal utility of additional units of that good declines. This produces a nice convex function which allows for only one optimal solution where the budget constraint is tangent to the indifference curve. Substitution of the two goods at the margin is assumed and consumers are willing to substitute more of the one good by less of the other goods. This is an abstraction which may not always hold, as Leontief-type indifference curves or lexicographic indifference curves illustrate (Figure 3.3).

Whether consumers move along a well defined demand curve is questionable and especially whether reactions can be assumed to be symmetric. Consumers may not have their preferences mapped in a consistent way and demand responses to rising prices may differ from the reaction to falling prices (see also Berkhout/Muskens/ Velthuijsen 2000). In other words, the price elasticity of demand may not to be the same for rising as for declining prices and it may not be stable over time. This issue turns out to be very important for estimates of the rebound effect.

When it is assumed that economic agents simply maximize “utility”, abstraction is probably overly high and too unspecific. Higher utility in the abstract sense is always better than lower utility, but from which products is utility derived from? With Leontief-type indifference curves only one combination of the two goods is efficient for the consumer, i.e. there is no trade off between the quantity of one good against the other.[8] Lexicographic indifference curves, very much in line with a hierarchy of needs approach, assume that consumers first consume one good (“other goods” in the right hand side diagram of Figure 3.3) until saturation is reached (at q_{OG}) before they start to consume (the natural resource in the example). Before q_{OG} is reached, consumption of the natural resource would simply provide no utility at all. Shelter and leisure activities may be a more intuitive example. Before shelter is not provided at sufficient levels, consumers do not derive utility from expenditures on leisure activities. Substitution and saturation issues will be important in the discussion further below, when likely effects of income growth are discussed in a multi product case. Clearly, the pattern of consumption changes with income and over time. Saturation may not occur as a general phenomenon, but in specific markets it surely occurs (e.g. Shapiro/Varian 1999).

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8 Since production is treated analytically similar to consumption, Leontief-type production functions may be more relevant in the former.

Although prices may affect consumption patterns, rising income does not simply raise demand for all products proportionally. We are not satisfied with ever more of the same products but instead shift to “luxuries” (products for which the income elasticity is greater than 1).[9]

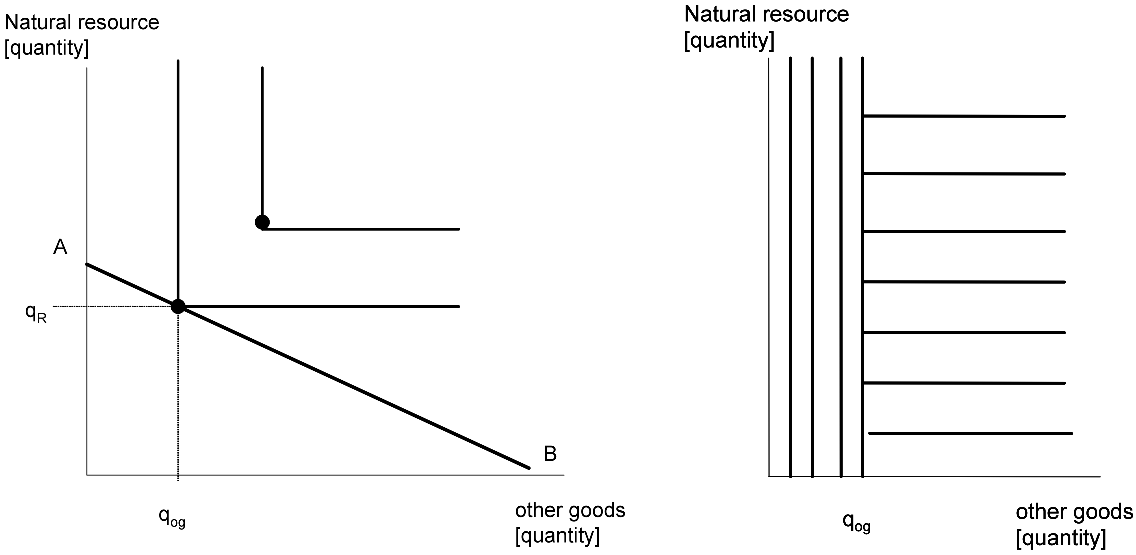

Figure 3.3: Leontief and lexicographic indifference curves

[9] For an analysis and discussion see Baumol (2001), Schettkat/Yocarini (2006), Kalwij/Machin (2007).

4 The rebound effect in production

Efficiency improvements in the use of natural resources in production — assuming that they are exogenous, i.e. costless — may affect the use of the resource through the substitution of inputs and/or through the demand for the product. Demand effects will depend on the share of the costs for the resource in overall production, which determines the possible price reduction, and the price elasticity of demand for that product. A high price elasticity (unsaturated market, price elasticity of demand >>1) of demand may raise the input of the resource substantially, whereas a low price elasticity will lead to a reduction of the input.[10] In the literature more attention has been given to the substitution effect and here especially to the possible substitution of energy by capital. Actually, a large amount of the literature analyzes whether natural resources (energy almost exclusively) and capital are substitutes or complements.[11] In the following, the basics of substitution effect analysis are discussed for a two-input and a multi-input production function. Finally, the relation between the use of natural resources and economic growth is discussed briefly.

4.1 Two input production function

So called Hicks-neutral technological change raises the productivity of all factors proportionally and thus allows to produce the same output using less inputs and leaving the input proportions unchanged. In Figure 4.1 the isoquants (Y1-Y1, Y1'-Y1') represent the same output but the isoquant closer to the origin is produced with a more efficient technology, i.e. less inputs. In a competitive market, companies will produce with the cost-minimizing combination of inputs, represented by q_R-q_{OI} $q_{R'}$-$q_{OI'}$, respectively. Analog to the budget constraint, the iso-cost line connects the costs of all factor combinations achievable with a certain budget. However, technological progress may not raise the productivity of inputs proportionally but it may be biased in the sense that one factor's productivity is rising more than that of the other factor. In this case, the isoquant will change its shape. In the middle diagram of Figure 4.1, technological progress raises the productivity of the natural resource more than the productivity of the other input. Assuming fixed prices, (i.e. a parallel shift of the is-cost line) the optimal factor combination will change using relatively more of the

10 Appelbaum and Schettkat (2001) developed this relation with respect to labor input showing that the rise in manufacturing employment until the early 1970s as well as subsequent decline common to all OECD countries can be well explained by different degrees of price elasticity.

11 In the theoretical extreme a 'substitution' relation between different inputs into production can mean that one input can totally substitute for other inputs, i.e. production is not conditional on the availability of one specific input.

natural resource which increased in productivity. For a given output level (Y1-Y1 = Y1'-Y1') less input is used but the ratio of inputs shifted to the factor which experienced an increase in productivity. The efficiency increase will raise the relative use of this factor. This substitution is the basis for the rebound effect in production, which raises the relative use of the input factor experiencing efficiency gains and which may raise the absolute amount of the usage of natural resources if growth processes occur.

However, the illustration in Figure 4.1 assumes that productivity improvements are exogenous or costless and prices remain unchanged, which is similar to a reduction of the real cost of the natural resource. In a neoclassical model inputs are used according to their marginal costs. If one factor increases in productivity, this factor will be used more instead of less because it is cost-minimizing to substitute for other relatively more costly inputs when prices are fixed[12]. Since perfect substitutability is assumed, a rise in the price of the natural resource (and thus a changed slope of the budget constraint) can compensate for the substitution effect as illustrated in the lower panel of Figure 4.1. A rising price for the natural resource, compensating the increase in efficiency, will leave the initial proportions of factor inputs unchanged. This is an important aspect because it touches the assumption that efficiency gains are exogenous and costless, which is usually not the case. It also shows that policies affecting the price can reduce or eliminate the rebound effect.

[12] The assumption of fixed input prices is also explicitly mentioned in Saunders (1992).

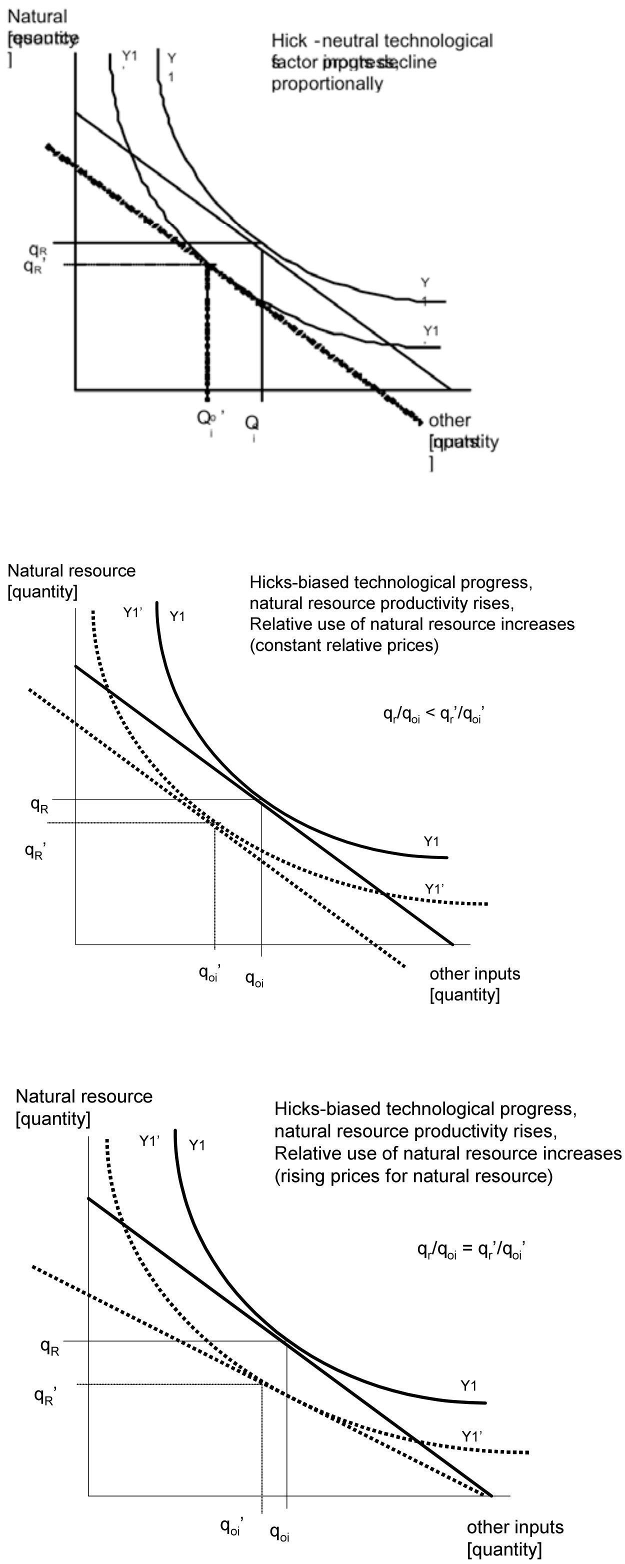

Figure 4.1: Hicks-neutral and biased technological change

4.2 Multiple input production function

It is important for the evaluation of rebound effects whether factor inputs are substitutes or complements, which is especially discussed among energy economists. Berndt and Wood (1975, 1979) argued that capital and energy may be complementary in a model with multi inputs production technology, although the two factors of production seem to be substitutes from the ‘engineering’ viewpoint. While an engine with better energy efficiency may be more costly than a less efficient engine, energy and capital may rise in tandem in a multi-input production model.[13] Berndt and Wood (and many follow-up studies) assume a production technology with four inputs –capital (K), energy (E), labor (L), and material (M) — and separability between capital and energy, labor and energy respectively, which may be interpreted that the optimal ratio of two factors is unaffected by the level of other inputs or that it is unaffected by the prices of other inputs.[14] They then use a ‘master production function’ with two composite inputs (capital/ energy and labor/material) to calculate the optimal combination of ‘utilized capital’ (which is the capital-energy composite input) and the labor/material composite input (master production function in the top left diagram (A) of Figure 4.2).

The optimal combination of the two composite inputs is determined in the conventional way, i.e. the iso-cost line is tangential to the isoquant. In the next step the optimal combination of energy and capital to produce ‘utilized capital’ (K’) is determined (top right diagram (B) in Figure 4.2), which has been labeled production sub-function by Berndt and Wood. If energy experiences an efficiency gain this will raise the relative amount of energy used to produce the greater amount of ‘utilized capital’ (a shift from K1 to K2, E1 to E2 respectively). Higher efficiency (lower costs) of energy thus translates into higher efficiency of the capital-labor composite (utilized capital), which will lead to a shift in favor of ‘utilized capital’ in the master production function (bottom left diagram (C) in Figure 4.2). On the level of the production sub-function this shift results in a higher demand for ‘utilized capital’ from K*1-K*1 to K*2-K*2 with capital input K3 and energy input E3. Thus as a result of the increase in energy efficiency alone, more capital and more energy will be used in the four-input production model, i.e. a net complementarity of energy and capital (Bottom right diagram (D) in Figure 4.2). Although Berndt and Wood provided a nice model demonstrating the possibility of counterintuitive effects their approach nevertheless hinges on several assumptions.

13 Berndt/Wood draw as policy conclusion from their analysis that capital subsidies may be viewed very critically to the extent that energy conservation becomes a conscious policy goal (1975: 267)

14 Substitution (complementarity) may be based on physical inputs (increasing use of one factor requires less (more) use of the other input (technical substitution)) or on economic reasoning (increasing use of one input if the price declines (rises) relative to the other inputs).

A particular weakness of Berndt and Wood is that they assume a single, homogenous output, whereas changes in prices will also affect the product mix demanded (J.L. Solow 1987). It has been argued that in the short run, a rise in energy prices will result in higher prices for energy intensive products and thus reduces demand and investment in these industries, which may appear as complementary between energy and capital (investment). But when long-living capital is replaced, more energy efficient equipment may be used implying a long-run substitutability between energy and capital (Miller 1986). Such an effect cannot be captured in time-series analysis, which focuses on short-term variations.

Broadstock, Hunt and Sorrell (2007) summarize the studies of the elasticity of substitution between capital and energy of over 200 empirical estimates as either weak complements or weak substitutes. They add, however, that ".. little confidence can be placed in this conclusion, given the diversity of the results and their apparent dependence upon the particular specification and assumptions used." (Broadstock/ Hunt/Sorrell, 2007: 50). A key weakness of these studies, they argue, is that specific restrictions are assumed rather than statistically tested.[15]

[15] The heterogeneity of estimates of the elasticity of substitution transfers to the models which rely on these estimates , such as computable general equilibrium (CGE) models.

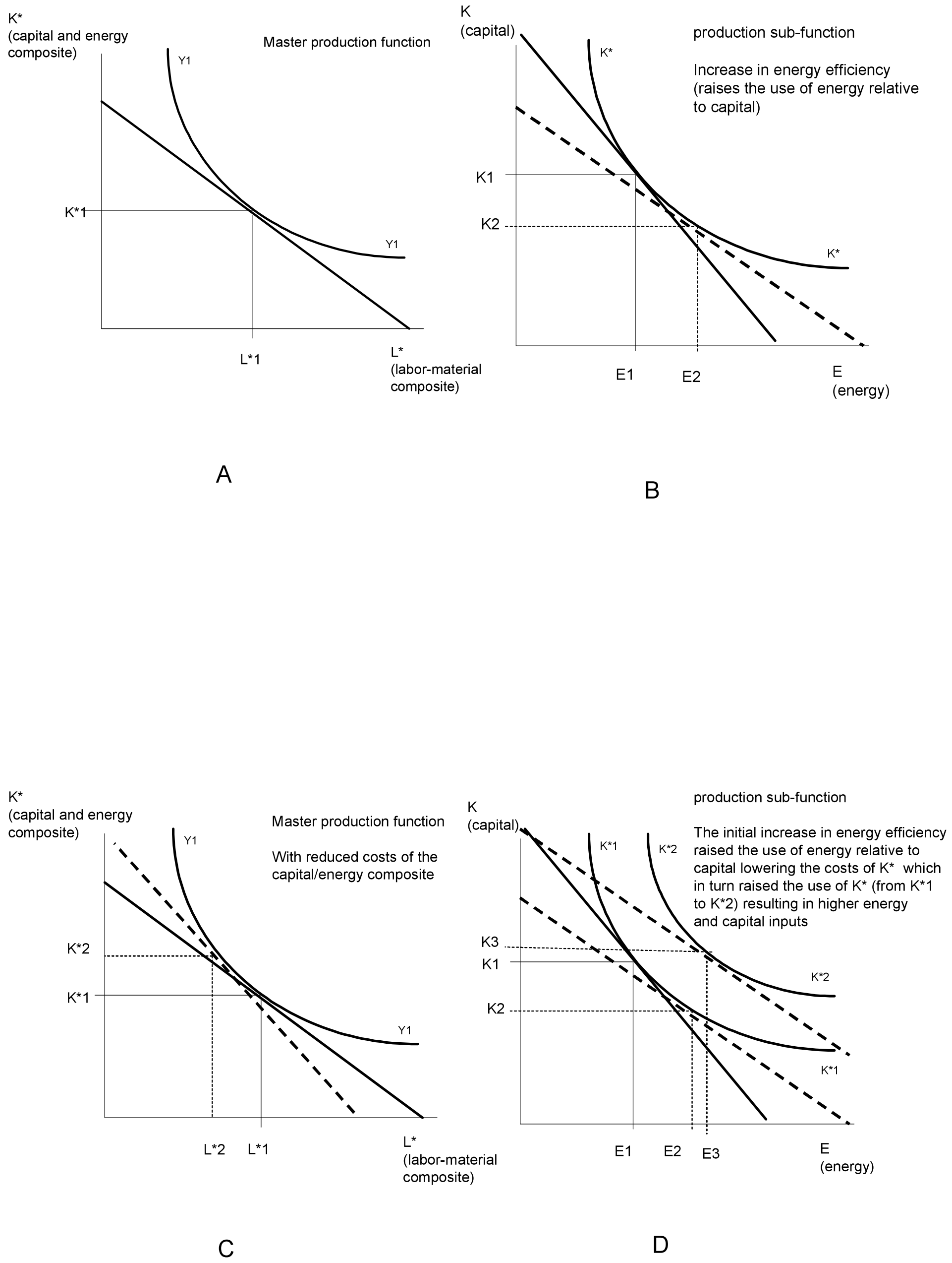

Figure 4.2: Substitution and complementarity in a multifactor production function (adaptation of Berndt/ Wood 1979)

4.3 Economic growth and rebound effects

The industrial revolution laid the basis for unprecedented economic growth in what became later the OECD countries. Industrialization was made possible by the steam engine based on coal, which was the general purpose technology identified as the driver of the first Kondratieff cycle. The discovery that increasing efficiency in the usage of coal led to more rather than less usage of coal was published by Jevons (1865), probably the first work on the "rebound effect". If gains in energy efficiency shift production inputs to energy and allow incomes to rise and if the additional income is spend on energy-intensive products "backfire" will occur.[16] "Energy using" technological change (Jorgenson 1984) seems to have dominated industrial development but this relation may have been strongly influenced by falling energy prices, i.e. a trend consistent with models that assume efficiency gains in the usage of natural resources to be exogenous and costless and thus lead to lower costs. Exogenous, costless efficiency gains, however, may no longer hold nor does the historic trend of declining prices for natural resources seem to be an appropriate assumption anymore, although we observed a decline of prices for natural resources as a response to the world-wide recession recently.

Some work on the environmental Kuznets curve suggests that the historic trend of the co-development of economic growth and energy consumption has ceased and that – cat least in the OECD countries — the two decoupled probably since the early 1970s (Grossman/Krueger 1994, Jänicke/Mönch/Binder, 1997). However, as Arrow et al., (1995) point out, the relationship may not hold for all resources[17] and it is not an automatic decoupling process. Structural change (the change in industry structure) contributed substantially to this trend since the expanding service industries seem to be much less energy (natural resource) intense than manufacturing. Although energy has been introduced into production function analysis (see above), these works assume substitutability between the various inputs and only take direct energy use into account.

Whether energy is regarded as direct or indirect depends on the level of aggregation: For final consumption the direct energy share may be small, but to encounter all energy necessary to produce the consumption goods the production chain must be taken into account. The energy content of intermediate products (embodied energy) needs to be added to the direct energy consumption at the final use.[18] Thus, the

[16] Nicolas Kaldor (1967) argued that manufacturing is the engine of growth along similar lines.

[17] The authors distinguish flows and stocks arguing that declining flows may still contribute to rising stocks.

[18] Since many consumption goods have investment good character, i.e. they are used over several periods, the time dimension is important when calculating overall energy consumption.

At the extreme, one might argue that all products are transformed energy and that also the energy content of labor needs to be taken into account.

system boundary applied[19] in the analysis is extremely important and the aggregation of micro-studies may suffer from a fallacy of composition most likely under-estimating total energy use.

Specific studies analyzing embodied energy in measures to improve energy efficiency find substantial effects: in the US forest industry, energy efficiency improvements are offset to 18– 83% by embodied energy (Kaufmann/ Azary Lee 1990); case studies of the share of embodied energy in buildings estimated 2–38% in the case of conventional buildings and 9–46% for low-energy buildings (Sartori/ Hestnes 2007). Thus, embodied energy seems to be important but as the cited estimates show, the variation is huge reflecting the methodological difficulties in defining the system boundary (especially the time horizon considered).

Estimated elasticities of substitution between capital and energy vary strongly with the assumed functional forms of the production function and assumptions about technological change. "The most striking result from the analysis is the lack of consensus that has been achieved to date, despite three decades of empirical work. While this may be expected if the degree of substitutability depends upon the sector, level of aggregation and time period analyzed, it is notable that several studies reached different conclusions for the same sector and time period, or for the same sector in different countries." (Sorrell/Dimitropoulos 2007: 51)

[19] The system boundary should, of course, not be drawn at country borders but should be open to include imports and exports.

5 Estimated direct rebound effects in consumption: the example of mobility

Clearly the consumption of fuel is not providing utility directly but only as an input in the production of mobility or other 'final services'. Thus, demand for fuel is derived demand depending on the demand for mobility[20], to stick to this example. Increased fuel efficiency reduces c.p. the costs per km traveled and probably induces higher demand for 'vehicle miles traveled' (VMT or M below)[21]. However, the c.p. assumption influences the results substantially. Some analysts assume that efficiency gains are exogenous or autonomous and are thus costless. Although there are differences in the energy content among the various sorts of oil, efficiency gains are usually related to improved fuel efficiency of engines, reduced weights of cars etc. Thus, these innovations will most likely depend on the price of fuel or, in other words, fuel efficiency gains are endogenous. Neglecting this endogeneity may bias estimates of rebound effects.

Although lower prices for VMT can induce a higher demand for traveling, the causation may also run in the reverse direction: Long distance commutes may lead consumers to select more fuel-efficient cars (although other aspects like comfort, security etc. may be relevant). Fuel cost is just one component in the cost function of VMT and in addition to the costs of the car itself, time is another important cost. The cost of time (or the scarcity)[22] may affect traveling substantially.

Probably the methodologically most advanced study on VMT has been performed by Small and van Dender (2005) who develop a simultaneous equation system for VMT, vehicle stock and fuel efficiency. They also control for the effect of regulation, the so called CAFE-regulation (Corporate Automobile Fuel Efficiency):

Vehicle miles traveled (M) depends on vehicle stock per adult (V), costs per mile traveled (P_M) and exogenous variables (X_M):

$$M = M(V, P_M, X_M) \qquad (1)$$

20 Of course, the example is defining mobility very narrowly.

21 Most studies refer to the US or the UK and therefore miles instead of km and VMT or M became common in literature. Vehicle miles traveled is the most common measure for mobility. Preferable over VMT might be person miles traveled but data restriction lead analysts to use VMT.

Vehicle stock per adult (V) depends on miles traveled (M), prices of new vehicles (P_V), price per mile (P_M), and exogenous variables (X_V):

$$V = V(M, P_V, P_M, X_V) \qquad (2)$$

Efficiency depends on miles traveled (M), price of fuel (P_F), regulatory measures (R_E) influencing the fleet-average fuel efficiency (like CAFE, corporate auto fuel efficiency) and exogenous variables (X_E):

$$E = E(M, P_F, R_E, X_E) \qquad (3)$$

Because the fuel costs per mile (P_M) is defined as fuel price (P_F) over efficiency of fuel use (E), efficiency is represented by fuel costs per mile P_M ($P_M \equiv P_F / E$). Substituting (2) into (1) gives:

$$M = M[V(M, P_V, P_M, X_V), P_M, X_M] \equiv M(P_M, P_V, X_M, X_V)$$

Small and van Denter report that their best estimates of the rebound effect for the US as a whole, over the period 1966-2001 are 4.7% for the short run and 22 .0% for the long run (see Table 5.1, upper shaded area). They find that the (direct) rebound effect depends strongly and negatively on income which is important because it substantially reduces the short-and long-run rebound effects to 2.6% and 12.1%. Using simple OLS estimates they find a substantially higher rebound effect (8.7% in the short-run, 33% in the long run) which they explain by endogeneity bias in OLS.

The overview of results in Table 5.1 shows variations in the estimated (direct) rebound effects, which seem to depend substantially on the estimation technique applied and the data used. Aggregate time series analysis seems to be biased if autocorrelation is explicitly considered (Greene 1992) and, of course, aggregate data is not the most appropriate to discover the effects. Aggregation — state level data — may also be a deficiency of the Small/van Denter analysis and micro data seems to be more appropriate to estimate direct rebound effects in consumption. Using pooled cross-section time series micro data the Greene/Kahn/Gibson study (lower shaded area in table 5.1) reports similar short-run and long-run rebound effects as Small and van Denter and a negative impact of the number of vehicles in the household on the rebound effect. This may be interpreted as a saturation effect. To be clear, a low rebound effect does not mean low consumption of fuel, it just means lower additional consumption of fuel.

[22] In economics the concept of 'opportunity costs', i.e. the utility or income derived from alternative activities, is used widely to capture the costs of time.

Small and van Denter find a strong inertia in their estimated usage equation, i.e. a large difference between the short-run and the long-run rebound effect because the vehicle stock is held constant. For changes in the stock of vehicles new-car prices and income are most relevant. They also find that efficiency is substantially negative and robustly affected by fuel costs which the authors interpret as consistent with a strong response to fuel prices when altering the efficiency by new-car purchases (Small/van Denter 2005: 17). This finding illustrates that efficiency gains are embodied.[23] They also find significant effects of CAFE (corporate automobile fuel efficiency) regulations. For the later part of the analyzed period they find substantially lower direct rebound effects indicating saturation in mobility.[24]

23 Indirect energy necessary to produce the new car is not accounted for.

24 Appelbaum and Schettkat (2001) argue that price elasticity declines along a linear demand function (saturation) which let demand for manufacturing products fall against demand for services.

Table 5.1: Econometric studies investigating the rebound effect of fuel price on VMT (vehicle miles traveled) in the US

Method	Rebound (direct) Short run	Long run	Period	Problem Characteristics	Author
Aggregate data					
Times-series	5-15%	12.7%	US 1957–1989	High autocorrelation	Greene (1992)
	11%	31%	US 1957–1990	Lagged dependent variables	Jones (1993)
	7%	29%		Dummies 1974, 1979 CAFE regulations time trend	Schimek (1996)
Pooled cross-section time series (panel)	16%	22%	1970–1991 50 US states		Haughton/Sarkar (1996)
	4.7% (8.2% OLS) **2.6% (1997–2001)**	**22% (33% OLS)** **12.1% (1997–2001)**	**1966-2001 36 observations in 50 US states**	**Simultaneous equation system**	**Small/van Dender (2005)**
Micro data					
Cross section	87% (across consumers)		1997 Consumer expenditure survey	Rebound strongly diminishing with income	West (2004)
	4% (across consumers)		1995 National Personal Transportation Survey		Pickrell/Schimek (1999)
Pooled cross-section time-series	20%	20%	1984–1990 Consumer expenditure survey	OLS	Goldberg (1998)
	23% 17% (3 vehicle household) 28% (1 vehicle household)	**23% 17% (3 vehicle household) 28% (1 vehicle household)**	**1979–1984 Residential Transportation Energy Consumption Survey**	**Simultaneous equation system**	**Greene/Kahn/ Gibson (1999)**

Source: Overview based on information in Small/van Dender (2005)

6 WI-research and concluding summary

6.1 WI-research

Past WI research was focusing on increases in resource efficiency, the relation between economic growth and the use of natural resources as well as on measures to promote conservationist goals. In this context, it has also taken the rebound effect into account. For example, research in the RG III (Material Flows and Resource Management) and RG II (Energy, Transport and Climate Policy) produced some quantitative estimates related to the rebound effect. Several WI publications investigate decoupling of the usage of natural resources and economic growth. Using material flow analysis Bringezu et al. (2004) test econometrically the functional relationship between DMI/cap (DMI = Direct Material Input per capita)[25] and GDP/cap [total material requirement/cap (TMR/cap) and GDP/cap] on the basis of national data (cross-section time series). They achieve mixed results but find a slight advantage of the quadratic model (inverted u-shape, although empirical data reflect only the increasing slope part, and the authors suggest to address this as “inverted L-shape”), i.e. that the usage of material per capita seems not to increase further after a certain level of GDP/cap is achieved. There is a general trend to relative decoupling and in some cases absolute decoupling (reunited Germany and US). When focusing on the domestic share of TMR a clear negative relationship occurs. “Obviously, economic growth is linked to a shift of resource requirements and associated environmental burden to other regions.” (Bringezu et al. 2004, 115). Among the high income countries TMR/cap, however, differs substantially indicating substantial flexibility in the usage of natural resources.

Also Bleischwitz and Steger (2007) find relative decoupling between the usage of natural resources per capita and GDP/cap, which implies a rising resource productivity. Also these authors emphasize the enormous international heterogeneity. At similar levels of GDP/cap the usage of natural resources differs substantially. In their 2008 paper, the same authors find absolute decoupling of the usage of natural resources (DMC) and GDP/cap for Germany, France and the UK but not for the US (where Bringezu et al. (2004) found absolute decoupling with regards to TMR). Obviously, the relation between economic growth and the usage of natural resources is not fixed but may change not least through regulation (Arrow et. al. 1995).

[25] DMI includes exported resources whereas DMC (Direct Material Consumption) excludes exports and focuses on resources used with the economy.

How shifts in the final demand structure may affect the use of natural resources is analyzed in a study by Acosta-Fernandez and Bringezu (1997). Using input-output analysis they investigate the hypothetical reduction in final demand for the twelve most resource intensive industries accompanied by a rise in final demand for the rest of the economy so that the structure of demand changes but the overall level of final demand remains unchanged. The shift of the final demand structure in favor of less resource intensive industries (10% of the output of the resource intensive industries) will reduce the usage of natural resources by 6%. I.e., a constant level of final demand is compatible with a reduction of the natural resource inputs (absolute decoupling).

Irrek and Thomas (2006) estimate the potential energy savings effects of 12 energy efficiency programs. They take a life-cycle approach, i.e. they estimated energy savings over the life-span of energy saving devices but they also take so-called embedded energy — the energy necessary to produce and install the devices — into account. They calculate substantial savings in energy expenditures which occur after the initial investments have been paid off. These savings in the energy bill result in substantial additional consumption (Figure 10, page 104). Based on a dynamic input-output model the indirect rebound effect (the sum of energy embedded in the energy saving devices plus energy use induced by additional consumption) to be 5.3% only. While the direct rebound effect is not calculated, the estimated figure of 5.3% for the indirect rebound effect is remarkably low, probably caused by substantial shifts in the structure of consumption (see above the result of Acosta-Fernandez and Bringezu).

Consumption patterns at the level of individual households are investigated in the "Living Lab project" (Lettenmeier/Liedtke 2008, RG IV) with the preliminary but absolutely astonishing result that within the same income classes the MIPS (material inputs per service unit) differ by a factor of 7 to 10. Again this result — although preliminary — suggests that difference in consumption patterns controlled for income can have an enormously different impact on the usage of natural resources.

6.2 Concluding summary

The above overview illustrates the complexity of the analysis of rebound effects. Rebound effects are a big question: Almost all variables are potentially relevant when investigating the economic reactions to efficiency gains in the usage of natural resources. No unified theoretical framework, which could capture the full complexity exists and therefore either partial effects are analyzed (like the direct rebound effect in consumption as a response to increased fuel efficiency) and/or strong theoretical assumptions are made, i.e. restrictions on the potential relations are assumed but usually not tested.

Partial analyses are extremely useful to understand the underlying behavioral processes but even if the direct rebound effect is estimated correctly — for the partial system — their results may not be easily aggregated to the overall rebound effect. Indirect rebound effects resulting from increased income (due to specific efficiency gains or a general rise in TFP, economic growth, respectively) open so many alternatives for spending that their impact on the usage of resources is extremely difficult to predict. Aggregate analysis of economy-wide or macroeconomic rebound effects may potentially overcome aggregation problems but at the same time it suffers from a lack of detail and usually from strong restrictions.

Therefore, not surprisingly, estimated rebound effects depend strongly on the theoretical framework and restrictions applied. The idealized neoclassical framework (together with auxiliary assumptions) inevitably concludes that rebound effects of an exogenous efficiency gain will be large because the direct rebound effect — due to substitution and income effects — will be substantial. Even if the direct rebound effect would be small (i.e. if markets are saturated (elasticity of demand <<1) and/or substitution is limited (elasticity of substitution <<1)) this line of reasoning concludes that additional real income resulting from higher productivity will cause a rebound effect often estimated to be 100% or more. However, several assumptions in this line of analyses may be questionable:

- Utility maximization is a very abstract concept basically resulting in "more is always better than less" but without referring to specific wants and needs
- Efficiency gains need to result in price reductions — as clearly recognized by neoclassical analysts (e.g., Saunders 1992)
- Efficiency gains will be used for higher demand/output
- Substitution between inputs may be very limited (at least in the short run)
- Markets may not be perfect, i.e. equilibrium may not be achieved. Adjustments are assumed to be fast (instantaneous), i.e. equilibrium is an applicable assumption
- Economic structure (demand and supply) may be important
- Efficiency gains may be endogenous
- …

Nevertheless, neoclassical analysis offers extremely useful insights helping to evaluate the bias caused by restrictive assumptions. For example, the multi-input production model developed by Berndt and Wood showed that the apparently substitutional relation between capital and energy may turn out to be complementary once substitution between capital-energy and other inputs are allowed for. Technical relationships, however, may differ from economic relationships and may severely restrict substitution.

A policy conclusion one may derive from neoclassical analysis could be that stimulating efficiency gains for conservation purposes is not very useful (inefficient) or even harmful (e.g., the core proposal of the Stern review is counterproductive). Instead economic growth needs to be reduced or stopped for conservation purposes. Another policy conclusion one may draw, however, is that rebound effects need to be limited by price policies (e.g. a tax on resources which experience efficiency gains). However, applying somewhat different assumptions than standard neoclassical analysis may lead to very different predictions of rebound effect and different policy conclusions.

1. Efficiency gains may not be exogenous and costless but rather endogenous and a response to rising prices of natural resources rather than a cause for price reductions.
2. The direct rebound effect may be limited because of limited substitution between inputs in production and/or saturated markets.
3. Utility functions may change, probably limiting the direct and indirect rebound effect.
4. Time constraints may affect the rebound effect ambiguously. On the one hand time can be a constraint for consumption (as in the VMT-analysis of Small and van Denter) on the other hand time constraints may induce the usage of time-saving equipment (to stick to the mobility example: travel by air instead of by train).
5. Natural resources are seldom consumed directly but usually in combination with some equipment.
6. Potential growth (productivity or TFP growth) may not be used for increased production (income) but may be consumed as leisure time (see 3.).
7. …

Rising income raises the demand for various products not proportionally, which in the past contributed to the shift away from manufacturing to service industries (Schettkat/ Yocarini 2006). This shift is equivalent to a shift from resource intensive to less resource intensive industries, which contributed substantially to the appearance of the environmental Kuznets curve. In this case the income effect contributes less to a rebound effect compared to a constant consumption mix and/or constant industry structure. Acutally, shifts in the structure of demand may lead to absolute decoupling of the usage of natural resources from economic growth. Figure 6.1 illustrates the income effect for consumption. The left diagram uses homothetic indifferences curves, i.e. rising income raises the demand for resource intensive and less resource intensive products proportionally (consumption of both products rises from A to B). In other words, the income elasticity for the two products is constant, independent of the level of income. For non-homothetic indifference curves preferences (income elasticities) are not independent of income and preferences may shift to the less resource intensive products as illustrated in the right hand side diagram of Figure 6.1.

As a result the same rise in income now shifts demand for of the less resource intensive product from A to C and even lowers the demand for the resource intensive product from A to C (in consumption analyses one would classify the resource intensive products as ‘necessities’ and the less resource intensive products as ‘luxuries’) in absolute terms. Most important, economic growth would reduce rather than increase the usage of natural resources. Not GDP growth as such is environmentally damaging but the structure of growth (Arrow et al.1995).

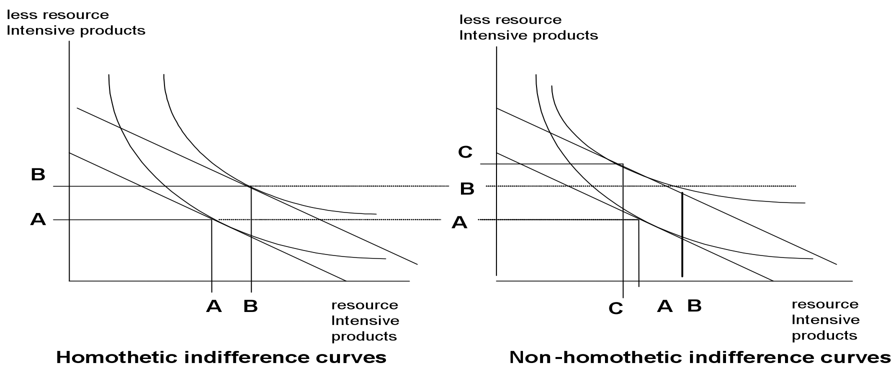

Figure 6.1: Income effect with homothetic and non-homothetic indifference curves

Efficiency gains may also be used for shorter working hours rather than for increased output. Whether that reduces or raises the rebound effect is ambiguous. Time — as opportunity costs — may limit the rebound effects as argued by Small and van Denter but time constraints may also initiate purchases of time saving equipment. On the other hand leisure time may be spend on resource intensive activities (so-called time rebound) or less resource intensive activities (motor boats and jet-skis vs. surfing), again, preferences may differ between individuals and may change over time (life styles).

The system boundaries — with respect to geographical area, time, stage of production — applied in the analysis of the rebound effect are extremely relevant. An overly restrictive definition of the geographical area will “export” parts of the rebound effect, a too narrow definition of the time period may over- or underestimate the rebound effect, focusing on a specific stage of production will leave substitution hidden along the production chain[26]. The embodied energy (natural resources) of

[26] In the extreme one may argue that capital is just “materialized energy”, very much in line with arguments reducing capital to materialized labor inputs (Pasinetti 1993).

capital (also capital used in consumption) therefore need to be taken into account and distributed over the life-cycle of the product.[27]

Consensus on the magnitude of rebound effects in production (here mainly concerning the elasticity of substation) or in consumption has not been reached so far. Comprehensive meta studies[28] which could systematize differences in the estimates have to my knowledge not been undertaken. The most comprehensive, systematic overview of the rebound literature has been published by the Energy Research Centre of the UK (UKERC). The authors of the paper conclude from their extremely careful, competent and comprehensive work that back fire is unlikely but that the economy-wide rebound effect will be at least 10% and may frequently exceed 50%. The direct rebound effect is likely to be less than 30% for household heating and cooling, transport (the latter probably closer to 10%) within developed countries[29] (Sorrell 2007). However, as stated very clearly, the UKERC research team regards most estimates as provisional and emphasizes that the methodology needs to be improved.

6.3 A framework for the analysis of rebound effects and open research

Given the limited knowledge about the rebound effect, the theoretical indeterminacy of many reactions, and the possibility for counterintuitive effects, an analytical framework should be open enough to discover and understand sources of and responses to efficiency gains in the usage of natural resources. Overly restrictive assumptions which may determine the results should, of course, be avoided but the major dimensions need to be included. Reduction of complexity is surely necessary but dimensions excluded from the analysis should be kept in mind when interpreting results especially in the formulation of political advice. The scheme displayed in Figure 6.2 may summarize the major dimensions.

Future research on the rebound effect should improve the understanding of adjustments following efficiency improvements and should test rather than assume behavioral aspects. Without any ambition to be comprehensive, some relevant research questions could include:

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27 Some analysts argue that the rebound effect of efficiency gains in energy use is small because energy is only a small cost component. This statement may not hold if embodied energy is taken into account.

28 In other areas of economics so called meta studies have been performed. See for monetary policy de Grauwe/ Costa Storti 2008.

29 For less developed countries rebound effects are assumed to be substantially higher.

Efficiency Gain

Endogenous
Embodied resources

Exogenous

Production
Substitution between inputs
Other changes
(productivity of other inputs, organization)
Total factor productivity
Price effects
Output effects

Consumption
Substitution between products
(relative price effect)
Spending of additional income
(income effect)
Preferences (changes of)
Time
(constraint for or cause of rebound effect)
Symmetry of the effects

Economy-wide (macroeconomic) effects
Structural change
Industry-specific and overall resource intensity

Figure 6.2: Major dimensions in the analysis of rebound effects

Related to consumption

- Consumer reactions to price changes (symmetric, asymmetric, constant?)
- Consumer reactions to price variations and information standards
- Consumer reaction to additional income
- Income, time and the use of natural resources (substitutes, complements?) Stability of utility functions?

Related to production

- Spillovers of efficiency gains (TFP)
- Embodied natural resources. Resource content of vertically integrated sectors (production chain)
- Changes in industry structure, consequences for the consumption of natural resources
- Exogenous vs. endogenous efficiency improvements
- Pricing behavior

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