Identification, quantification, and containment of energy-efficiency induced rebound effects: a research agenda rebound research report 1

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Identification, quantification, and containment of energy-efficiency induced rebound effects: A research agenda

Rebound Research Report 1

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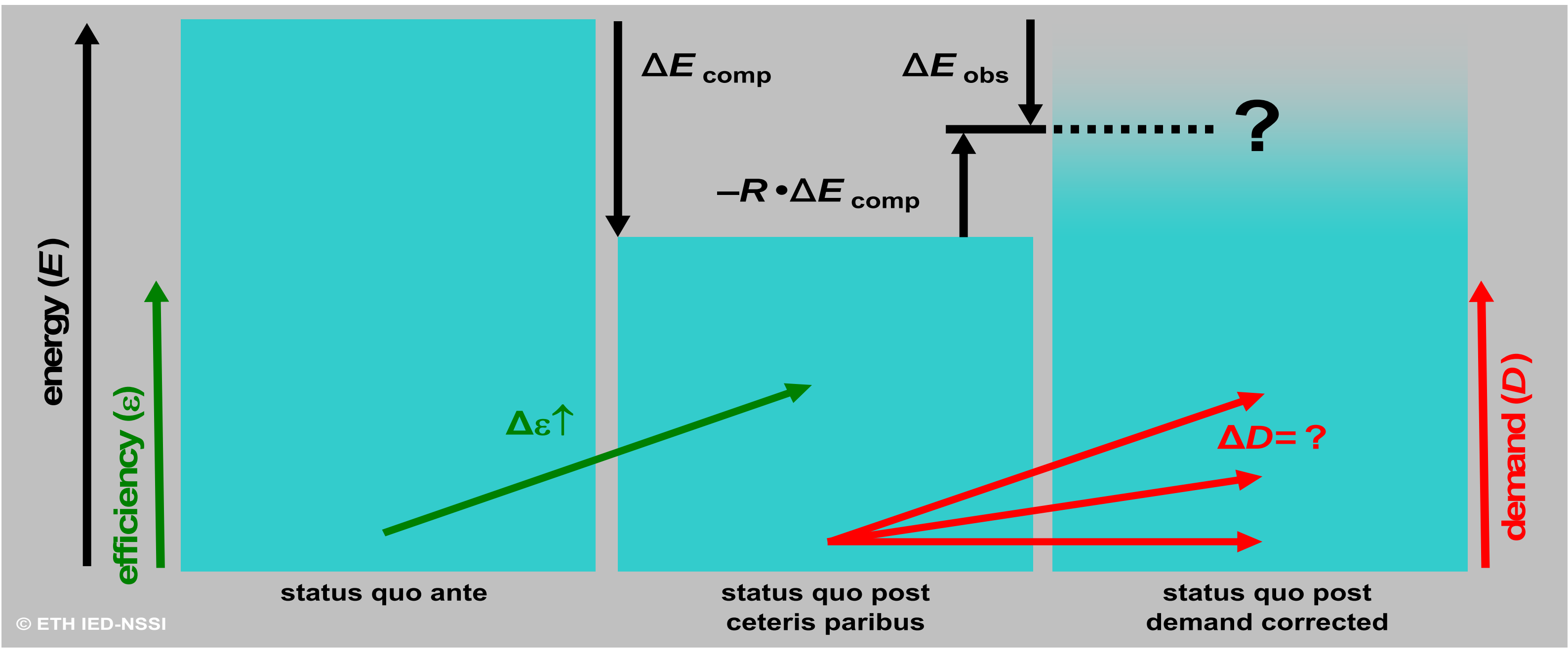

IED – Institute for Environmental Decisions
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Abstract

The introduction of more efficient products or services is often accompanied by rebound effects, which counteract the positive effect of increased efficiency. For example, newly built highways as well as improved train services lead to higher transportation demand. The definition, identification and quantification of rebound effects (also called take-back effect or backfire) are areas of ongoing research. If a product or service becomes more efficient (regarding energy use or the use of some other resource, like time or space), this increased efficiency itself might give rise to increased demand. Generally, induced rebound effects appear in three different manifestations: Increased demand for the same service as it has become cheaper (direct rebound effect), increased demand for other services as money (i.e., purchasing power) has become available (indirect rebound effect; also called secondary rebound effect or income effect), and structural effects on larger parts of the economy due to changed demand, production and distribution patterns (macro-scale rebound effect; also called economy-wide rebound effect). In parallel to these manifestations, which account for the type of good the additional demand is for, also we differentiate three different causal mechanisms for the different ways how rebound effects might become induced (economic, socio-psychological, and regulatory rebound effects). The occurrence of rebound effects can drastically reduce the environmental efficiency of new technologies. This report lines out the current state of science and existing scientific niches, and proceeds by formulating research questions to be addressed by future rebound research at IED-NSSI. These research questions concentrate on three areas. First, understanding, quantifying and containing rebound effects associated with governmental policies. Second, tools for and recommendations regarding the integration of rebound effects into LCA. At present in most LCA studies the ceteris paribus assumption is adopted, which might to overly optimistic results, as new products are likely to change demand. In principle at least direct rebound effects should be introduced into LCA studies. Third, investigation of rebound effects associated with the purchase of hybrid vehicles, in particular mileage rebound.

Keywords

Rebound effects, take-back effect, income rebound, energy-efficiency, households, consumer behavior, energy policy, LCA, hybrid vehicles

1 Introduction

1.1 Introduction

Whether new products and technologies will successfully penetrate the market, is in principle ruled by the market economy. Governmental interventions are not necessary in principle. However, in cases where the product or technology in question is associated with relevant external costs, and where a new product or technology has the potential to lower these externalities, the question arises whether a governmental subsidy or other market intervention can be justified, i.e. whether it would be both effective and efficient. In fact, for many innovations in the field of environmental protection, greenhouse gas emissions and non-renewable resources, the presence of important externalities regularly invokes calls for governmental promotion.

In many cases, life-cycle inventory (LCI) and life-cycle assessment (LCA) methodologies are applied in order to compare two alternative technologies, with the final goal to answer the question whether a governmental market intervention in favor of one of those technologies would be beneficial. Both LCI and LCA analyses call for the definition of a so-called "functional unit", which often is chosen in the form of the product or service at stake, i.e. "energy per heated square meter" or "energy pro vehicle kilometer". With the choice of such a functional unit, an implicit "ceteris paribus" assumption comes along, i.e. it is assumed that demand for the technology or service in question will remain unaffected by the change in energy-efficiency.

This assumption seems not to hold true in all cases. For example, for the retrofitting of space heating in Austrian multi-family dwellings, a rebound effect of 30% has been reported. This means that only 70% of the ex-ante estimation of energy savings actually was observable ex-post (Figure 1). Apparently, the higher energy-efficiency of the service "space heating" induces a higher demand; possible explanations are higher nocturnal and daytime temperatures, non-activation of temperature reduction during vacational leaves, and changes in the socio-demographic structure of inhabitants due to increased monthly rent fees after retrofitting.

Building number	Initial energy consumption (kWh/m^2 yr)	Calculated energy consumption after retrofit (kWh/m^2 yr)	Actual energy consumption after retrofit (kWh/m^2 yr)	Calculated savings (%)	Actual savings (%)	Rebound Share (%)
1	203	144	168	29	17	41
2	218	161	176	26	19	27
3	185	132	147	29	20	29
4	218	167	198	24	9	61
5	193	127	150	34	23	34
6	169	108	122	36	28	22
7	168	116	115	31	31	0
8	148	91	97	39	35	11
9	239	140	172	41	28	32
10	179	134	144	25	20	23
11	159	117	141	26	11	57
Average	189	129	148	32	22	30

Figure 1. Results of an empirical investigation of the energy conservation effect of building and heating system retrofit (multi-family dwellings only) (reproduced from Haas and Biermayr 2000).

In the case of energy-efficient cars, one might also hypothesize that higher fuel economy might induce higher demand for vehicle kilometers. In contrast to the well-known elasticities which describe demand changes due to changes in price level, rebound research deals with demand changes (actually, energy demand changes) due to changes in energy-efficiency (or, in the case of rebound in time, time efficiency).

1.2 Definition

The introduction of more efficient products is often accompanied by rebound effects, which counteract the positive effect of increased efficiency. The rebound effect is a concept developed in energy economics. In the policy debate, the general notion of the rebound effect is that a technical or policy measure produces secondary effects which at least in part off-set the initial, positive effect of the primary measure, so that the measure is less effective in achieving the primary policy goal. The definition, identification and quantification of rebound effects are areas of ongoing research (Greening et al. 2000; Grepperud and Rasmussen 2000). Its precise definition varies among researchers, but the common denominator is that if a product or service becomes more efficient (regarding energy use or the use of some other resource), it will also become cheaper, which might give rise to increased demand (in Section 2.1 we will introduce our differentiation of three different causal mechanisms that might induce rebound effects): The rebound effect is the behavioral response to cost reductions of energy services as a result of energy efficiency gains. The behavioral response, for economists, includes changes in purchasing behavior as a result of changes in market prices.

The rebound effect is also called take-back effect, backfire effect, or Khazzoom-Brookes effect (after the founding publications Khazzoom [1980] and Brookes [1978]). The term was first applied narrowly to the direct increase in demand for an energy service whose supply had increased as a result of improvements in technical energy efficiency (Khazzoom 1980). It has later been differentiated and expanded to include indirect and economy-wide effects. Greening et al. (2000) and Berkhout et al. (2000) distinguish three different categories of rebound effects (after de Haan et al. 2005 and Hertwich 2003):

> Direct rebound effects: increased demand for the same service/product. This includes the direct effect or pure price effect. This effect is comprised of the substitution effect (i.e. the increase of demand for an energy service which becomes cheaper as a result of the increase in energy efficiency, i.e. the rebound as originally defined by Khazzoom), and the income effect (i.e. the increase in available income as a result of the reduced price of the energy service, which leads to other, energy consuming purchases).

> Indirect (secondary) rebound effects: increased demand for other services as money (i.e., purchasing power) has become available. Also, technical energy efficiency improvements reduce the cost of energy services to industry, which leads to price reductions of goods and services and hence increased demand. This has also been termed the general equilibrium effect.

> Macro-scale rebound effects (also called economy-wide effects, transformational effects): Structural effects on larger parts of the economy due to changed demand, production and distribution patterns. This includes market-clearing price, quantity adjustments (especially in fuel markets), and changes in technology that have the potential to change consumers' preferences, alter social institutions, and rearrange the organization of production.

For example, if the energy efficiency of a car is increased by technological innovations, 100 km can be driven with less fuel and hence at a lower cost. This lower cost could have the consequence that people consume more car services (direct rebound effect), by (i) drive more often; (ii) driving longer trips; (iii) switching to larger cars, (iv) buying additional cars. The lower cost could also trigger recreational activities (indirect rebound effect), which in turn will lead to an adaptation of the over-all economic system (macro-scale effect).

Identification of occurrence, and, if present, quantification of rebound effects are generally not straightforward. Most empirical studies focus on the direct rebound effects, because the other effects are difficult to isolate. Most work has been done on the effects of the introduction of energy-saving technologies, e.g., space heating (Haas and Biermayr 2000). Greening et al. (2000) present a survey of studies in the United States which indicates that the rebound effect is somewhere between 0 (for white goods) and 50% (for space cooling), but typically less then 30% (space heating,

lighting, automotive transport). Schipper and Grubb (2000) review studies covering 80–90% of energy use in OECD countries and find that the rebound is on the order of 5–15%. They also review the issue of economy-wide effects and find no evidence for substantial macro effects.
As Hertwich (2003) points out, indirect (secondary) effects imply that energy efficiency leads to growth, from the perspective of economic policy makers not an undesired result. Energy efficiency therefore could indeed substantially contribute to growth, and therefore increase the amount of goods and services consumed.
Rebound effects induced by costs savings were the first to be investigated and originate in economics, especially energy economics. In close analogy, also time savings (Jalas 2002; Spielmann et al. 2008) and the reduction of socio-psychological costs of ownership (as postulated in de Haan et al. 2006b) might be regarded as possible drivers for rebound effects. As example for the latter, it may well be not the financial but the socio-psychological cost-of-ownership (due to neighborhood pressure, norms of a peer group, etc.) that prevents people from buying sport-utility vehicles (SUV) (de Haan et al. 2006b).

1.3 Notation

On the macroeconomic level, the rebound effect is defined based on the elasticity of total final energy demand with respect to changes in energy-efficiency (other meanings of the term rebound occur in medical sciences and in sports [basketball]). A commonly used synonym to rebound effect is *take-back* effect. Another term, backfire effect, is sometimes used for rebound effects exceeding 100% (see below).
In neoclassical approaches, one can express the output of an economy, in terms of its gross domestic product (GDP), through a generalized production function *f*, with the classical production factors as independent variables,

$$GDP = f(C, L, E, R) \tag{1}$$

where C denotes the invested capital stock, L the amount of labour, and E the amount of final (end) energy used. Examples for the use of other non-renawable resources, denoted as R are land occupation, metals, rare elements, spice metals, etc. In the case of energy, the distinction between E (secondary energy carriers) and R (primary energy carriers) sometimes proves difficult, but this is of no relevance to the rebound discussion.
The amount of secondary (final) energy, E_i, needed to produce a given product or service, denoted as "energy service" ES_i, can be computed as

$$ES_i = E_i \cdot \tau_{E_i} \tag{2}$$

where τ_{E_i} ist he energy efficiency of the conversion of the secondary energy carrier to the „energy service". The elasticity of E_i with respect to changes in τ_{E_i} then is (for the sake of simplicity, we now drop index i),

$$\eta_{\tau_E}^{E} = \frac{\Delta E / E_0}{\Delta \tau_E / \tau_{E_0}} = \frac{d \ln E}{d \ln \tau_E} \tag{3}$$

Here, the case $\eta_{\tau_E}^{E} = 0$ is called (perfect) inelasticity, and $\eta_{\tau_E}^{E} = -1$ is unit elasticity. In most cases, however, $-1 \le \eta_{\tau_E}^{E} \le 0$ applies. For tight system boundaries (i.e. without allowing for substitution effects with other services or products that potentially also are affected by changes in τ_E), the cases $\eta_{\tau_E}^{E} < -1$ and $\eta_{\tau_E}^{E} > 0$ can be regarded as impossible; but for broader system boundaries, they may in fact occur.
The rebound effect now can be defined as

$$R = 1 + \eta_{\tau_E}^{E} \tag{4}$$

In analogy to the above cases, the following distinctions can be made

$R = 0$: no rebound effect (observed energy savings equal ex-ante engineering estimation)

$0 < R < 1$: rebound effect present (energy savings > 0, but smaller than theoretical savings)

$R = 1$: rebound effect 100% (despite higher energy-efficiency, no change in final energy demand).

Again, the two extreme cases hardly occur in real settings, but are allowed for by theory:

$R < 0$: negative rebound (energy savings exceed theoretical savings)

$R > 1$: rebound larger than 100% (despite higher efficiency, an increase in energy demand is observed)

The case $R > 1$ i soften referred to as *back-fire* effect.

1.4 Illustrative example

In the following we illustrate energy-efficiency induced rebound effects with the example of dishwashers (Figure 2). Improved technology would yield significant energy savings under the assumption of unchanged demand, however the improved efficiency will give rise to substitution effects and income effects. In addition to these monetary rebound effects, also rebound effects due to reduced psychological costs could take place, if the higher energy-efficiency causes consumers to adapt their attitudes towards dishwashers. In the case of dishwashers, the significant improvements in efficiency over the last 15 years probably have lead to an increase, rather than a decrease, of total energy demand for dishwashing machines, as these machines in the meanwhile have become an integrating part of almost any household kitchen.

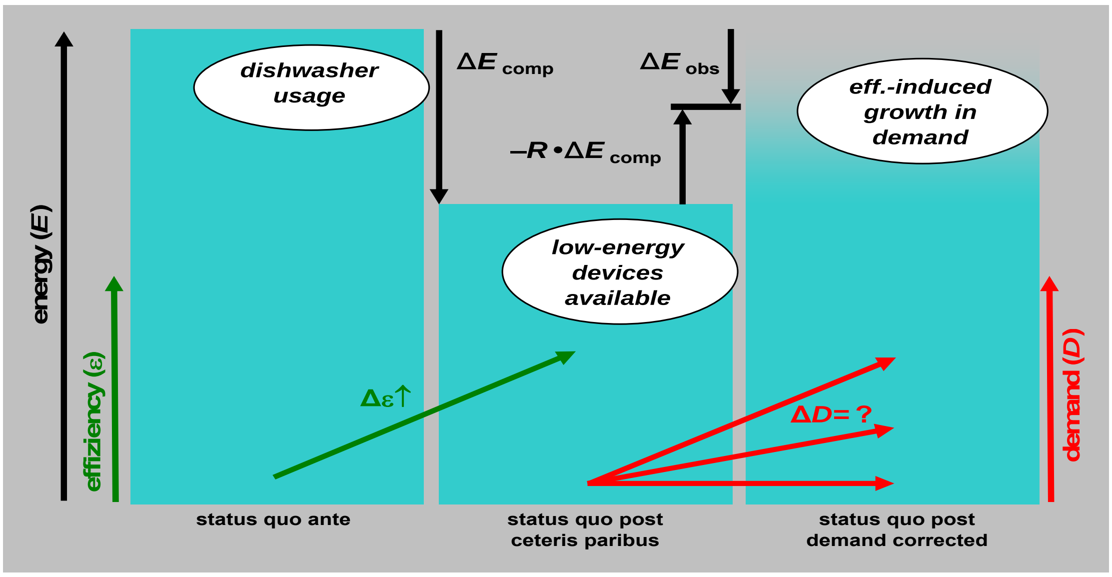

Figure 2. Illustrative example of energy-efficiency induced rebound effects. The introduction of a new technology or service with improved energy-efficiency, $\Delta\varepsilon > 0$, will result in a new system state where total energy demand fort he technology or service in question is reduced by ΔE_{comp}, assuming constant demand. (status quo post, with so-called ceteris paribus assumption). Depending on substitution effects (e.g. replacement of manual dishwashing) and income effects (lower energy costs generate additional purchasing power for e.g. inviting friends for dinner and, consequently, more dishwasher demand), an energy-efficiency induced demand change, $\Delta D > 0$, might take place. As a result, only an energy saving $\Delta E_{obs} < \Delta E_{comp}$ will be observable. The rebound effect in this case is $R = (\Delta E_{comp} - \Delta E_{obs}) / \Delta E_{comp}$.

1.5 Recommendations from UK ERC

Below we reproduce the overall conclusions of the Sorrel (2007) report, which we regard as the state of science and as general guideline for our future research.

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

- Energy efficiency may be encouraged through policies that raise energy prices, such as carbon taxes, or through non-price policies such as building regulations. Both should continue to play an important role in energy and climate policy. However, many official and independent appraisals of such policies have undoubtedly overstated the contribution of non-price policies to reducing energy consumption and carbon emissions.

- It would be wrong to assume that, in the absence of evidence, rebound effects are so small that they can be disregarded. Under some circumstances (e.g. energy efficient technologies that significantly improve the productivity of energy intensive industries) economy-wide rebound effects may exceed 50% and could potentially increase energy consumption in the long-term. In other circumstances (e.g. energy efficiency

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

- Rebound effects vary widely between different technologies, sectors and income groups. While these differences cannot be quantified with much confidence, there should be scope for including estimated effects within policy appraisals and using these estimates to target policies more effectively. Where rebound effects are expected to be large, there may be a greater need for policies that increase energy prices.

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

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

- Carbon/energy pricing can reduce direct and indirect rebound effects by ensuring that the cost of energy services remains relatively constant while energy efficiency improves. Carbon/energy pricing needs to increase over time at a rate sufficient to accommodate both income growth and rebound effects, simply to prevent carbon emissions from increasing. It needs to increase more rapidly if emissions are to be reduced.

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

1.6 Cornerstones for research on rebound effects at IED-NSSI

At present, energy in the form of its various secondary carriers (electricity, natural gas, heating oil/diesel, gasoline, etc.) still has to be considered as relatively cheap (in mid 2008, as the price for a Brent quality barrel of oil surpassed the level of USD 100, in real prices the cost of oil was equivalent to oil prices during the 2nd oil crisis in 1983). Increases in price levels for energy will lead to some decrease in demand, but will also induce that consumers become more aware of energy costs and will lead to a higher importance of energy costs in consumption decisions. Therefore, increases in energy prices will exhibit an increase of rebound effects. Research on rebound effects is therefore expected to increase in importance over the next, say, 5 years.

The energy-efficiency and technology diffusion group at ETH Zurich's Institute for Environmental Decisions, Natural and Social Science Interface chair, therefore started a research focus on the identification, quantification and containment of energy-efficiency induced rebound effects. Research has already been done on time rebound (Spielmann et al. 2008) and on the vehicle ownership rebound for hybrid vehicle buyers (de Haan et al. 2006a, 2007). The following overarching research questions will be common to most activities within this line of research:

> Which system boundaries are adequate;
> How can rebound effects empirically be measured or there magnitude be estimated by other methods;
> In which cases should rebound effects be taken into account;
> How to do so.

However it is clear already today, that rebound effects will not become as common to "daily science" as e.g. LCA itself has become. Rebound effects will always suffer from disputable and partly deliberate system boundaries and will never be able to be fully separated from other effects (wealth increase, changes in use of energy services and technologies, etc.). But it should be possible to establish some basic rules in order to identify those cases where rebound effects are likely to be of importance and be dominant to the overall result. In most if not all concrete policy cases, it should be able to adopt a policy design that contains and minimizes the magnitude of possible rebound effects. This is closely related to the question in which cases energy policies should primarily target (relative) energy efficiency (promotion of energy efficient technologies), and in which cases the internalization of external costs of (fossil) energy use, i.e. CO_2 and energy taxes, are to be preferred. It is the aim of our research to formulate conclusions and guidelines for energy policies with regard to the containment of rebound effects. In the field of the further development of LCA methodologies, it is the aim to give guidance with respect to the identification of case studies where the ceteris paribus assumption does not hold and rebound effects have to be accounted for in the case of technology assessment.

In the following sections, we line out our research foci, on the containment of rebound effects in energy policy, partly funded by the Swiss Federal Office for Energy (Section 2), on the integration of rebound effects into life-cycle assessment, partly funded by the Swiss National Science Foundation (Section 3), and on rebound effects associated with hybrid vehicle ownership, performed in collaboration with the Swiss importers of hybrid vehicles Honda automobiles (Suisse) SA, Toyota, and the Lexus Division of Toyota (Section 4).

2 Identification, quantification, and containment of rebound effects in energy policy

2.1 Three causal mechanisms for rebound effects, with specific examples and conclusions

The macroeconomic definition of the rebound effect, as given in Chapter 1, is based on the elasticity of final energy demand with respect to changes in energy-efficiency. This is a purely descriptive metric that does not allow for causal interpretations. The macroeconomic definition also does not allow separating the total rebound effect into direct, indirect, and economy-wide macro rebound effects. For this, one has to switch to the microeconomic level. In this section, we therefore differentiate three possible causal mechanisms that can give rise to rebound effects. Moving towards causality also means distinguishing between drivers for human behavior. Price signals are one of those drivers, but there are others. In the following, we will discuss monetary, socio-psychological, and institutional drivers separately.

We differentiate between three possible causal mechanisms for energy-efficiency induced rebound effects:

> Economic (monetary) rebound: The higher demand is caused by price signals, i.e. by the sum of substitution effects and income rebound. This is the classical causal driver for rebound effects mostly dealt with in literature and in empirical microeconomic field studies to identify and quantify rebound effects. However, this causal mechanism requires that in fact money is saved and the increase in energy-efficiency does lead to saved energy costs, corrected for higher investment costs. Normally, more efficient technologies or services have lower operating costs, but higher investment costs (were that not the case, a classical win-win situation would be present). In rebound research it is important to account for the higher investment costs. It has to be kept in mind that in purchase decisions individual consumers often do not correctly compute total costs of ownership. Individuals use to high discount rates and weight the present (investment costs) too high in comparison to the future (running energy costs). The other side of the mirror, however, which may occur especially within the context of human decisions specifically aiming at reducing energy costs, is that any change in investment costs is simply ignored and considered as not relevant to the environmental decision the individual is about to make ("that is another matter"). This can in part be described by the psychological effect called mental accounting, and by the characteristics of human decision making under uncertainty; the Prospect Theory of Kahneman and Tversky unifies these effects among others. If an income rebound effect does occur only due to wrong discount rates or due to mental accounting (i.e., the consumer thinks he is net saving costs, and therefore starts spending more, but in fact he ignored the higher investment and is not net saving anything at all), for us this is not an economic rebound, but a socio-psychological rebound effect instead.

As introduced above, the rebound effect is defined as a function of (final) energy demand elasticity with regard to changes in energy efficiency. This is a purely descriptive measure that can in principle be determined empirically; this definition does not differentiate for different possible causes. Whereas it is generally implied that there should be a price signal (induced by increase energy efficiency) in order for the demand response to come into existence, it might well be that innovative technologies have higher energy efficiency and hence lower energy bills, but need higher investments and have identical cost of ownership, such that for the rational consumer there is no net price signal induced by the new technology. If the consumer would, however, undervalue investment costs, i.e. have different preference weights for investment money than for energy bill money, he or she might perceive a price signal (towards the innovative technology) all the same. If, on the other hand, a consumer applies too high discount rates and values the present much higher than the future, he or she might overvalue the additional investments and also perceive a price signal (towards conventional technology). It should be noted that the definition of the rebound effect for itself does not state that a price signal should be present, it merely builds upon changes in energy demand due to changes in energy efficiency. Price changes are the most investigated, widely accepted intermediate variable here, but other mechanisms could be present for so-called "bounded rational" decision makers and for so-called "imperfect markets". In our research we therefore distinguish three different possible causal mechanisms that are suited to induce rebound effects:

(i) *Income rebound* ("economic rebound", "rebound induced by rational price signal"): The increased demand for the energy service that has become more energy-efficient is due to economic reasoning only. This causal chain applies if the higher investment costs for the energy service with the better energy-efficiency do not fully compensate financial savings due to lower energy bills (and any tax cuts, incentives, etc.).

(ii) *Socio-psychological rebound*. The increased demand is due to reduced socio-psychological costs of ownership or usage for the energy service with the better energy efficiency. This effect will be present in most cases where the above-mentioned income rebound occurs, as consumers hardly ever exhibit fully rational decision making and often do not have precise knowledge about energy prices, pay-back periods, etc. Consumer decision making with regard to energy-intensive services is characterized by rules-of-thumb, heuristic decision approaches, and only rough, if at all, knowledge on total energy costs.

(iii) *Regulatory rebound*. The increased demand is induced by certain regulatory details; the regulatory rebound does not comprise of all rebound effects due to governmental action, but only due to technical definitions that ofter have been formulated „in favor of" new, energy-efficient technologies, therefore providing them with competitive advantages, which induce additional demand.

Examples are

(i) Income rebound examples:
Ex. 1: Increased demand for lighting services due to energy-efficient fluorescent bulbs (either more bulbs being installed, or more lumen being installed, or extended operation time).
Ex. 2: Reduced investment in isolation of buildings due to more efficient heating, for example heat pumps that allow for reduction isolation thickness or increased total glass surface compared to the case when a conventional heating system would have been chosen.

(ii) Socio-psychological rebound examples:
Ex. 3: Purchase of sport-utility vehicles (SUV) with hybrid powertrain in neighborhoods or social networks where the possession of an SUV with conventional powertrain would be sanctioned.

(iii) Regulatory rebound examples:
Ex. 4: In „Minergie" certified buildings more heating power can be installed if a heat pump solution is chosen, because the electrical power needed for heat pump operation is balanced with a factor of 2 only, where a factor of 3 would have been correct out thermodynamical reasoning;
Ex. 5: As the energy label for whiteware is relative, i.e. the size of e.g. a refrigerator is accounted for when computing the energy-efficiency, such that a larger refrigerator will receive a better energy-efficiency rating if it uses the same amount of power compared to another, smaller refrigerator, consumers might purchase larger appliances as they try to purchase energy-efficiency class "A" whiteware only.
Ex. 6: Incentives, tax cuts and subsidies for electrical bikes might well not reduce the total mileage of conventional motor bikes, but in of bicycles instead. And subsidies or other policies promoting small, electrical cars might well be faced with the effect that they are reducing the share of bicycles, but not of conventional passenger cars.

With regard to the potential to arrive at recommendations for energy policy, the following conclusions for the three causal effects of rebound effects can be formulated:

(i) The *income rebound*, based on the homo oeconomicus concept, cannot be avoided, as it is part of rational behavior of actors in a market economy thriving for optimal allocation of all production factors. However, the income rebound effect should be integrated into any ex-ante policy analysis and the forecasting of effects of future policies. Main "entry point" is the analysis of substitution rates between production factors, i.e. whether capital or labor can be substituted by energy services if the latter become more efficient. Main question to be answered is in which cases energy policy should focus on energy and/or CO_2 taxes, and in which cases energy policy should concentrate on promoting market penetration of innovative, energy-efficient technologies.

(ii) The *socio-psychological rebound* also cannot be expected to be avoidable in total, but it is possible in principle to become reduced by means of improved information, transparency, education, changes to the design of incentive schemes, etc. All of these measures might be used to change the decision making behavior of bounded rational individuals towards the „homo oeconomicus" concept. Main points of departure are that consumers weigh prices differently according to the periodicity and payment method (daily out-of-the-pocket expenses, like gasoline costs, are weighed more then the annual car tax bill), according to the level of perceived control (car repair costs due to accidents are perceived as out of control and mostly not part of any „mass transit vs. own car" cost comparison), and according to the transaction partner (being eligible for tax rebates might induce larger behavioral changes than direct rebates on the product price). All of these "psychology of the perception of money" effects might induce rebound effects due to perceived price signals, even though a price signal in fact is not present when performing proper financial computations including all cost components and applying realistic discount rates for future payments.

(iii) The *regulatory rebound*, finally, being defined as residual rebound effect that cannot be attributed to either income rebound or socio-psychological rebound, in principle can be reduced in magnitude, and it will be the main target of policy optimization measures to do so. Of course not all rebound effects induced by governmental action are classified as regulatory rebound; rather governmental action can induce income rebound effects, socio-psychological rebound effects as well as regulatory rebound effects. With careful policy design and precise definition of criteria for tax cuts and subsidies the regulatory rebound can be minimized. The government can either introduce taxes on energy (or other resources) or on labor, or it can subsidize certain technologies or set minimal standards for others. In the case of taxes, regulatory rebounds may emerge if increases in demand occur for products for which efficiency standards have been introduced. However in most cases the other two types of rebound causes are expected to be dominant. In the case of subsidies for energy-efficient new technologies, regulatory rebound effects might emerge because for every subsidy and standard, technical definitions, minimal targets, and conversion factors have to be set. Such definitions are almost never optimal; there might be a general tendency from the side of policy makers to set such values "in favor of" the new technologies to be promoted. This will then inevitably lead to demand increases that are to be identified as regulatory rebound effects.

Table 1 shows the application of the above categories of different causal mechanisms: The causal mechanisms are complementary to, and not alternative to, the commonly applied differentiation of rebound effects into different goods or services for which the increased demand has occurred.

types of increased demand ↓ / causal mechanisms for rebound →		economic rebound $	socio-psychological rebound Ψ	regulatory rebound §
Saunders 2000	Sorrel 2007			
direct rebound	direct rebound (income/output eff.)	increased demand for the same good or service (Saunders 2000) income/output effects (Sorrel 2007)		
indirect rebound	direct rebound (substitution eff.)	increased demand for other goods/services (Saunders 2000) substitution effect (Sorrel 2007)		
macro-level rebound	indirect rebound	adaptation of production system to new demand patterns (Saunders 2000) secondary and grey energy effects (Sorrel 2007)		
Holds for resource rebound effects in general, in special for energy rebound (increased demand due to increased energy-efficiency) and time rebound (increased demand due to increased time-efficiency)				

Table 1. Differentiation of total observable rebound effect according to different types of increased demand, both in the Saunders (2000) and Sorrel (2007) categorizations, and according to different causal mechanisms.

2.2 Resulting rationale for research

We identify and focus on the following research questions:

> Under which circumstances is it advisable for the government to subsidize or otherwise promote a given energy-efficient new technology or service (and, if advisable, by which means and policy tools)?

> For which circumstances is there a risk that governmental interventions will be associated with adverse effects due to high rebound potential?

> Which preferences do households have, and to which restrictions do they feel subjected, and which state of knowledge regarding relevant energy costs and consequences of behavioral options do they have? Do household members apply intersectorial compensation strategies?

> Basis to address the above questions is the investigation of the question, how households adjust their consumption patterns after experiencing savings in energy costs of, say, CHF 1000 to 2000 annually.

3 Integration of Rebound Effects into Life-Cycle Assessment

3.1 Using LCA for assessment of new technologies

Life-Cycle Assessment (LCA) over the last three decades has become widely accepted and today is the method-of-choice for the assessment of the ecological consequences of human activity. Environmental impacts caused by products or services can be made more comparable to each other with the help of LCA. Also, the introduction of new technologies is often assessed using LCA. In the field of transportation, for example, the environmental benefits and consequences of new fuels, new powertrains, and completely new transport systems have in the past and at present been assessed using LCA. The introduction of more efficient products or services is often accompanied by rebound effects, which counteract the positive effect of increased efficiency. For example, newly built highways as well as improved train services lead to higher transportation demand. The definition, identification and quantification of rebound effects (also called take-back effect or backfire) are areas of ongoing research. If a product or service becomes more efficient (regarding energy use or the use of some other resource, like time or space), it will also become cheaper, which might give rise to increased demand. Generally, three different rebound effects might be induced: increased demand for the same service as it has become cheaper (direct rebound effect), increased demand for other services as money (i.e., purchasing power) has become available (indirect rebound effect; also called secondary rebound effect), and structural effects on larger parts of the economy due to changed demand, production and distribution patterns (macro-scale rebound effect; also called economy-wide rebound effect). The occurrence of rebound effects can drastically reduce the environmental efficiency of new technologies. In principle, therefore, at least direct rebound effects should be introduced into LCA studies. However, at present in almost all cases the ceteris paribus assumption is adopted: It is assumed that apart from the new technology or service, everything else, including the demand side, will not chance.

3.2 Past and future of LCA

Life cycle approaches for the assessment of environmental impacts of goods and services have their origin in technology assessment. In the past three decades, the science of Life-Cycle Assessment (LCA) methodology and procedure has grown and developed significantly, and has undergone a shift from single facility focus to a view of product supply chains. Various methodological problems in LCA have been dealt with (Ekvall 2002): For example, the definition of system boundaries, allocation, the modeling of waste management processes, weighting methods, data quality and uncertainty, and methods for assessing land use in the context of LCA.

Parallel to the scientific development, and often integrated into it, many initiatives have been taken to harmonize LCA methodology. These finally resulted in harmonization efforts on a global level within the international organization of standardization (ISO), leading to a series of international standards for LCA: ISO 14040–14043, which was a milestone for LCA practice. This built consensus on methodology, approaches and procedures is rather unique for an environmental assessment method. However, the standard regulates far from every methodological choice in an LCA. In fact, it allows for producing virtually any LCA result. This common basis for the application of LCA has the potential to be quite polyvalent. Indeed it can be a valid tool for integrating product-related decision making, and for gaining insight into

environmental hot spots, opportunities, and trade-offs. And since the LCA methodology develops rapidly, the standard becomes outdated fairly quickly.
As state-of-the art develops, guidelines and standards need to be adjusted. After Ekvall (2002), interesting developments since the mid 1990s include methods for geographically dependent impact assessment: The effect of a pollutant often depends strongly on where, when, and how it is emitted. This is typically not taken into account in a life-cycle impact assessment. However, approaches that take geographical aspects into account have been presented for the assessment of, e.g., acidification and ecotoxicological effects.
Another interesting development is the distinction between two types of LCA: attributional and consequential LCA. An attributional LCA aims at describing the environmental properties of a life-cycle and its subsystems. A consequential LCA aims at describing the effects of changes within the life-cycle.

3.3 On attributional vs. consequentional LCA

The distinction between two different types of LCA, attributional LCA and consequential LCA, each with a different aim or application area, substantially reduces some of the persistent methodological problems in the life-cycle inventory analysis (LCI). These include the definition of system boundaries, allocation problems, and the choice between average and marginal data:
> Attributional LCA aims at describing the environmental properties of a life cycle and its subsystems;
> Consequential LCA aims at describing the effects of changes within the life cycle. This makes consequential LCA the more likely candidate to investigate rebound effects.
In the following we rely on the reasoning of Ekvall (2002), who in an editorial drafted the future research needs within LCA. Certain decision-makers can be more interested in knowledge on environmental properties of systems (generated by attributional LCA) than in knowledge on the effects of changes within the life cycle (generated by consequential LCA). Of course, decision-makers need to be informed about the consequences of decisions. This constitutes a strong argument in favor of consequential LCA. There are, however, limitations to consequential LCA regarding accuracy (Ekvall 2002): The effects of changes depend on economic mechanisms, that consequential LCAs only begin to model. Models of such mechanisms might alleviate this problem: Partial equilibrium models can improve the knowledge of what product flows are affected by a change (Bouman et al. 2000). General equilibrium models can give insights on rebound effects (Ibenholt 2002). These make up the most prominent options currently existing for improvements in the methodology of consequential LCA, if the aim is to generate as complete and accurate description of consequences as possible.
To accurately model the effects of an increased demand for a product in the life-cycle investigated, it is necessary to account for effects on the market of this product. These effects depend on how sensitive the supply and demand are to changes in the price of the product. They also depend on how easily the product can be substituted for other products, and on what products are likely to be the substitutes. Such aspects are included in economic partial equilibrium models. Hence, a solution might be to integrate partial equilibrium models into the life-cycle inventory analysis (LCI). Bouman et al. (2000) state that different types of models generate different and complementary types of information.
Consequential LCA only begins to model such mechanisms. To describe more aspects of these consequences, like rebound effects, it is necessary to integrate more of economic theory into the LCI. In this process, LCA researchers can probably learn from energy systems modeling. The experience from integrating knowledge on technology and economic theory is extensive in this area.
Dynamic optimizing models is one of the tools that integrate knowledge on technology and economy in energy systems modeling. Following Ekvall (2002), such models can be relevant for effect-oriented cleaner production tools. In particular, they can be used for generating information on marginal effects in dynamic production systems. In theory, at least, this information is more accurate than the information generated through static models. Rebound effects can occur, for example, when a cost-efficient change is made to make the use of resources more efficient. The savings in costs makes it possible to increase the total economic activity. Such an increase results in a demand for the resource that — partly or

completely — offsets the savings obtained through the original change. The increased economic activity is, of course, also likely to increase the demand for other resources. Current LCAs are far from modeling these effects, but valuable insights can be generated through a general equilibrium model. This is a macroeconomic model of a complete economy based on the assumption that all markets that make up the economy either are in or tend towards a state where the supply of each product equals the demand for that product.

Hence a possible way to model rebound and similar effects in an LCA seems to be to link the process tree of the LCA to a general equilibrium model. The process tree is a bottom-up model in the sense that it starts from unit processes. Macroeconomic models are top-down models because they start from the perspective of the total economy (Ibenholt 2002). The pros and cons of bottom-up and top-down models have been debated in the field of energy economics (Wene 1996). To overcome some of the weaknesses and utilize the advantages of both approaches, attempts have been made to link the two (Hoffmann et al. 1996, Wene 1996).

3.4 Resulting rationale for research

Our rationale arises from the identification of LCA research needs as laid down by Ekvall (2002), and a more specific proposal by Hertwich (2003), that the rebound effect in connection with sustainable consumption is defined as the secondary behavioral response to a primary sustainable consumption measure. What is of interest to sustainable consumption research is how to address the rebound effect, and the benefits we can expect from this.

- How do consumers change their behavior in other areas as a result of adapting one example of sustainable consumption? One hypothesis is that of a spill-over effect. When people accept the concept of consuming responsible for one item, they are more likely to accept this also for other items. Another hypothesis is a conscience-soothing effect. People may commute to work on public transport, but in compensation they feel entitled to fly to far-away vacation spots.
- What is the measurable impact of a sustainable consumption measure from a life-cycle perspective? How can it be assessed? The life-cycle assessment of a single measure, comparing e.g. conventional and fair-trade coffee, could not capture this effect. The assessment of the entire household budget, as it has been pioneered in energy analysis, however, can "take care" of the rebound effect.

We propose a new research approach which combines the assessment of direct and indirect environmental pressures using a combination of (hybrid) LCA, general equilibrium modeling, and consumer expenditure surveys with a case study method for comparing examples of sustainable consumption with conventional consumer behavior.

The area of environmental systems modeling can learn from the experience of energy systems modeling. There are two fundamentally different approaches to linking models (after Ekvall 2002): Softlinking means that the results from one model are manually fed into the other. A number of iterations can be performed where both models are manually tuned to be consistent with each other. Hardlinking means that the models are integrated to become, in essence, a single computer model. According to Wene (1996), softlinking is the most practical starting point. Keeping the two models separate increases transparency, and the iterations in the softlinking procedure contributes to the learning process. This means that more can be learned from softlinking. Hardlinking, on the other hand, makes it possible to produce more results since the automatic calculations are quicker. For this reason, Wene argues, hardlinking is the preferred end result. Hardlinking also produces a unique and completely consistent solution whereas the iterations of softlinking depend onsubjective choices and may result in solutions that are not fully consistent.

The goals of the present project proposal therefore are to develop a methodology to test for the presence of direct and indirect rebound effects, and then to develop a guideline in which types of LCA (which type of case study, size of system boundary, etc.) which levels of rebounds effects (direct, indirect, macro-scale) should be incorporated. We then want to adopt and illustrate the proposed method and guideline for two case studies: We will test for, and, if present, quantify direct and indirect rebound effects, and apply a full LCA for both, rebound effects in public transport (e.g. effect of better train services on the demand), and for rebound effects in individual motoring (e.g. effect of high fuel-efficiency on car demand and usage). Two surveys will be conducted; first a survey of 1000 Swiss households on the effect of faster and

better train services, for which we will target train users before and after the improvement of train services with the new train time table as of mid-December 2006 in Switzerland; second, a survey of again 1000 Swiss households that recently bought a new, highly fuel-efficient passenger car, on the effect of the availability of highly fuel-efficient cars on the demand for car services: (a) number of trips; (b) length of trips; (c) car used for trip; (d) number of cars owned.
As more aspects of reality are included in a model, the model becomes more complex. This tends to make it more difficult to understand why the model gives a specific result. Even when the model is formally transparent, i.e., when all input data and relationships are presented, it might not be transparent in practice. This has become a problem as LCAs grow more detailed. It is also a problem in complex energy systems models, and it can be expected to be a problem if additional tools based on economic theory are integrated into consequential LCA. As indicated by Wene (1996), the problem might be reduced if the different models are joined by softlinking. Another, complimentary strategy is to make the models less complex by excluding aspects of reality that are not crucial to the question at hand.
With our methodology to be developed, for the first time, product LCAs will no longer be restricted to the assessment of environmental impact per unit function served (e.g. 1 person kilometre driven) but include expected rebound effects in an adequate way.

4 Rebound effects associated with hybrid vehicles

4.1 Previous work

Hybrid powertrains are considered being a promising technology to decrease fuel consumption of passenger cars. Sales numbers of hybrid cars are expected to rise considerable until 2010. However, the introduction of more efficient products is often accompanied by rebound effects, which counteract the positive effect of increased efficiency. Three kinds of direct rebound effects could possibly occur when buying hybrid cars: (i) people could tend to switch from small and/or already fuel-efficient cars to the new hybrid car, (ii) the average vehicle ownership could increase, if the hybrid car is often purchased without disposing of an already owned vehicle, and (iii) the number of miles driven could increase. Previous studies (de Haan et al., 2007, 2006b, 2006a) have determined that rebound effects accompanying hybrid car purchases in the Swiss population occur neither for vehicle size nor for vehicle ownership.

4.2 Resulting rationale for research

The principal aim of future research is to gain insight into the previously unexamined rebound effect: The amount of kilometers driven. This will further establish whether hybrid vehicles such as the Lexus RX400h should rightly be considered a technology effective in lowering overall CO_2 emissions in the population investigated. In addition, various energy policy measures across European countries aimed at promoting hybrid sales shall be compared and discussed in reference to the results of the principle aim of this study, whether hybrid cars show a vehicle kilometer rebound in the Swiss population.

The data to be used for this assignment originates from a follow-up survey sent to Swiss owners of the hybrid Lexus RX400h and owners of the similar non-hybrid RX300 which serve as the control group. The original more elaborate survey was sent to the same people 12 months earlier. The cornerstone of this second survey consists of the participants' odometer readings of all cars owned as it allows direct computation of vehicle kilometers driven in the time between the two surveys and comparison between groups.

Various statistical tests shall be conducted upon these data in order to determine whether the purchase of such a hybrid vehicle leads to an increase in kilometers driven, compared to the control group. Additional data from the follow-up survey shall be evaluated also, such as the amount of cars disposed of or purchased in addition to the Lexus car, and put into comparison with the data from the first survey.

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