AIP Conference Proceedings

Energy efficiency, human behavior, and economic growth: Challenges to cutting energy demand to sustainable levels

Tilman Santarius

Citation: AIP Conference Proceedings **1652**, 70 (2015); doi: 10.1063/1.4916170
View online: http://dx.doi.org/10.1063/1.4916170
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1652?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
Ecology versus economic growth in europe: How to improve relative efficiency?
AIP Conf. Proc. **1648**, 720015 (2015); 10.1063/1.4912952

Sustainable production of energy from microalgae: Review of culturing systems, economics, and modelling
J. Renewable Sustainable Energy **7**, 012701 (2015); 10.1063/1.4906919

The relationship between economic growth and biomass energy consumption
J. Renewable Sustainable Energy **4**, 023113 (2012); 10.1063/1.3699617

Can large-scale advanced-adiabatic compressed air energy storage be justified economically in an age of sustainable energy?
J. Renewable Sustainable Energy **1**, 033102 (2009); 10.1063/1.3139449

Energy Use Can Be Cut by Efficiency, Survey Says
Phys. Today

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32

Energy Efficiency, Human Behavior, and Economic Growth: Challenges to Cutting Energy Demand to Sustainable Levels

Tilman Santarius*

Visiting Scholar, Institute of European Studies and Energy and Resources Group, University of California, Berkeley,
310 Barrows Hall, Berkeley, CA 94720-3050

Abstract. Increasing energy efficiency in households, transportation, industries, and services is an important strategy to reduce energy service demand to levels that allow the steep reduction of greenhouse gases, and a full fledged switch of energy systems to a renewable basis. Yet, technological efficiency improvements may generate so-called rebound effects, which may 'eat up' parts of the technical savings potential. This article provides a comprehensive review of existing research on these effects, raises critiques, and points out open questions. It introduces micro-economic rebound effect and suggests extending consumer-side analysis to incorporate potential 'psychological rebound effects.' It then discusses meso-economic rebound effects, i.e. producer-side and market-level rebounds, which so far have achieved little attention in the literature. Finally, the article critically reviews evidence for macro-economic rebound effects as energy efficiency-induced economic growth impacts. For all three categories, the article summarizes assessments of their potential quantitative scope, while pointing out remaining methodological weaknesses and open questions. As a rough "rule of thumb", in the long term and on gross average, only half the technical savings potential of across-the-board efficiency improvements may actually be achieved in the real world. Policies that aim at cutting energy service demand to sustainable levels are well advised to take due note of detrimental behavioral and economic growth impacts, and should foster policies and measures that can contain them.

Keywords: energy and human behavior, consumption growth, rebound effect.

INTRODUCTION

It is now widely agreed across the scientific and political spectrum that modern industrialized societies must shift their energy systems from a fossil to a renewable basis, and reduce greenhouse gas emissions by about 80% to 90% until 2050, compared to 1990 levels [1]. In order to realize this tremendous challenge in a cost-effective manner, it is an important strategy to raise energy efficiency across the board of the entire economy—from household heating and cooling, electrical appliances, personal and commercial transportation, to industrial processes. In fact, various scenarios anticipate that taking full advantage of technological energy efficiency potentials may cut energy service demand by 50% to 70% compared to business-as-usual, which would much facilitate the transition to renewable energies and the achievement of emissions reduction targets (see, e.g., [1] [2]; [3]; [4]; for the European Union:[5]; [6]).

Yet debate remains about whether it is realistic to assume full realization of technical efficiency potentials in the real world. Most notably, human behavior as well as economic growth may increase energy service demand and hence 'eat up' parts of the technical savings potential. This effect is called a 'rebound effect'. Rebound effects occur if a reduction of inputs per unit of output (efficiency) generates an absolute increase in output. It is well understood in both economics and the wider public that the principle of 'economic optimization' can be achieved either by minimizing the inputs per unit of output, or by maximizing the output at given inputs. Hence there is little doubt that any productivity improvement of the economy would lead to overall economic growth, and hence overall production and demand. Yet in the field of energy economics and politics, the rebound effect remains a matter of recurrent and ambiguous debate, both in scientific and in public debates.

Estimates on the overall quantitative dimension of rebound effects are extremely heterogeneous. At one end of the spectrum, it is stated, "*most of the economic growth of our Western civilization in the past 200 years stems from the rebound effect*"([7], p 233). In a similar vein, other rebound researchers believe that improvements in energy conversion technologies would contribute to increasing economy-wide energy demand over and above the initial level—a phenomenon that is known as *backfire* (e.g. [8], [9], [10], [11]; etc.). At the other end of the spectrum, it is stated, "*the concept of a nontrivial rebound (...) is without basis in either theory or experience. It is, I believe, now widely accepted to be a fallacy...*" ([12], p 161; similarly, and more recently, [13]). Other authors who do not deny

---

* Correspondence to: tilman@santarius.de; www.santarius.de/en

Physics of Sustainable Energy III (PSE III)
AIP Conf. Proc. 1652, 70-81 (2015); doi: 10.1063/1.4916170
© 2015 AIP Publishing LLC 978-0-7354-1294-1/$30.00

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32

the rebound effect in principle estimate that its practical significance is low (e.g. [14]; [15]; [16]). It is clear that clarification of these different assessments is of great importance to research as well as to political design of a transformation of energy systems.

This article reviews theory and empirical evidence of rebound effects in the literature, attempts to identify deficiencies and blind spots in current rebound research, and suggests how rebound effects can be better understood, and eventually calculated, in the future. So far, two research strands can be distinguished: Micro-economic rebound effects describe the relationship between efficiency improvements and energy demand at the level of consumers and households. Therefore, in the following, micro-economic rebound effects are mainly considered as consumer-side rebounds. On the other hand, macro-economic rebound effects describe the relationship between energy efficiency improvements, and overall economic growth and energy demand. These rebound effects are therefore understood as energy efficiency-induced economic growth-effects. They are to be clearly distinguished from other factors and determinants of overall economic growth, such as improvements in labor or capital productivity. Besides critically reviewing findings from both these research strands, this article proposes that rebound effects at the 'meso-economic level', ie, producer-side-rebounds and energy price-rebounds, should be at the center of future rebound analysis, too.

CONSUMER-SIDE REBOUND EFFECTS

The debate on micro-economic rebound effects was kicked off in the 1980s by Khazzoom [17, 18]. Already in his first publication, Khazzoom points out that energy efficiency improvements may reduce the costs of running energy-using goods and services. If that is the case, by buying an energy-efficient technology, consumers can effectively increase their net income. This income effect can be used either to increase the utilization rate, the stock, or the comfort of the respective goods and services, which increases overall energy demand. This is called a 'direct rebound effect'.

However, Khazzoom admitted that any real income does not necessarily have to be spent in its entirety to increase demand of the respective goods and services. It is also conceivable that people use their extra income for the purchase, or intensified use, of other goods and services, including the procurement of additional efficiency technologies for saving energy elsewhere. However, this then generates so-called 'indirect rebound effects'. For the production and use of virtually every kind of good or service generates some amount of energy consumption. Hence Khazzoom has postulated that the price elasticities of demand are the decisive criteria for both the general appearance as well as the scope of direct rebound effects ([17], p 22).

The greater the price elasticity of demand, the more will consumers change their energy service demand when the energy price or utilization costs are reduced. For rebound effects, this means: at no price elasticity, no direct rebound effects will occur; at a price elasticity $0<e<1$, direct rebounds below 100% occur, at elasticities $e>1$, backfire occurs. This relationship was confirmed by a large number of publications (e.g. [18], [19], [20], [21], etc.). Note that rebound effects are always measured as the percentage of the theoretical, technical savings potential that has been 'eaten up' by increased demand.

In addition to the increase in demand due to income effects, any reduction in costs can also bring about a substitution of other products and services by those more efficient. Such substitution effects may also be expected if there is no absolute income effect. For example, if driving a car with a given MPG initially is more expensive than traveling by public transportation, an efficiency improvement can make car travels cheaper compared to public transportation, which will lead to a substitution of public transportation journeys by car journeys — even if capital costs for purchasing the more efficient car were high and prevent an overall income effect to occur. Accordingly, indirect rebound effects depend on substitution and cross-price elasticities.

Scope of Consumer-side Rebound Effects

In the past 30 years, several dozen empirical studies have been published that compute the quantitative extent of micro-economic rebound effects in different sectors using econometric models or historical data series. The overwhelming number of studies refers to industrialized countries. Five meta-analyses provide an overview and an evaluation of the numerous individual empirical studies [21], [22], [23], [24], [25]). These studies cautiously extrapolate that direct rebound effects at the level of consumers/households on average amount to about 25% [25] or range between 10% and 30% [24], with levels probably closer to 10% for personal automotive transportation particularly in the USA, and levels around 20% and 30% for personal automotive transportation in other countries, as well as space heating and space cooling (see Table 1) This means that direct rebound effects on average nullify about 10% to 30% of the technical efficiency savings potential.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32

TABLE 1: Overview of economic estimates of direct consumer-side rebound effects Sources: [26], [21], [22], [23], [21], [25]

Sector / energy service	Range of results
Personal transportation	5 – 87%
Household illumination	5 – 12 %
Space heating	1 – 60%
Space cooling	0 – 50%
Water heating	10 – 40%
Others (e.g., household appliances)	0 – 49%

In addition, the consumption of any kinds of other goods from real income gains will on average amount to indirect rebound effects. Assuming a) that households on average spend between 5% and 10% of their total expenditures on energy, and b) that households spend any income gains equally on their existing consumer portfolio, such income effects will generate indirect rebounds in the order of 5% to 10%, respectively (see also [14], [24]).

Elasticities and Rational Choice in the Real World

As described above, both theoretical as well as most empirical studies use elasticities as the key variables for explaining and calculating rebound effects. On closer inspection, empirical estimates on the basis of price and substitution elasticities should be treated carefully. First, much of the knowledge about elasticities, particularly for older rebound studies from the 1980s and 1990s, has been derived at times of historically low energy prices. It seems likely that at times of rising energy prices, elasticities may change significantly. Secondly, empirical studies usually assume that elasticities are symmetrical. Yet in reality they will often be rather asymmetrical. For example, consumers might react with a stronger decrease of demand when energy *prices* increase, e.g., fuel prices at the petrol station, while they might react with less strong an increase of demand when energy *costs* decrease, e.g. after the purchase of a more efficient car [25]. However, one study on rebounds in the transport sector in Germany considered asymmetrical elasticities and arrives at high rebounds, nevertheless [26].

Thirdly, it is unlikely that elasticities in reality will be uniform for all consumers and remain constant over time. For example, they can vary with the financial strength of users: consumers of lower income groups may react more strongly to cost-cutting efficiency increases with an increase in demand, than consumers of higher income groups, who have already met their needs [27]. That means, as overall income rises, the amount of direct rebound effects is likely to decrease. In addition, consumption of certain products or services can approach points of saturation; accordingly, the scope of direct rebound effects would decline [28], [14]). However, elasticities can also grow in the long run, because the horizon of possible policy options for consumers constantly increases [18]. For instance, a person who commutes to work every day may not immediately drive more when he/she buys a more efficient car. Yet once cost savings for commuting are significant, this person may consider moving further away from the workplace, which instantaneously changes the elasticity of demand.

Given these arguments, it is but a broad-brushed assumption that elasticities in reality are steady and constant. Constant elasticities also imply complete reversibility of investments at all times, which will rarely be given in reality. In particular, energy-intensive technologies such as cars, house heating systems, or building insulation are marked by a high degree of irreversibility—at least in the short and medium term; consumers are not going to demolish their low-energy homes because energy prices plummeted. Research needs to be conducted that systematically investigates potential combinations of income and substitution elasticities on a product-, user- , price-, and time-specific basis. Overall, the above-mentioned critiques suggest that elasticity-based calculations rather overestimate the scope of direct rebound effects.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32

Technological Change and Consumer Preferences

At the same time, a more robust determination of direct rebound effects requires to better understand consumer preferences and behavior. For one, efficiency improvements cannot only reduce the energy consumed per unit, but also of other factors such as time or money. For example, Binswanger [20], Jalas [29] and Santarius [30] show that energy efficiency improvements that save consumer's time can generate large rebound effects—in particular where time as a 'household production factor' is scarcer than money.

Moreover, efficiency improvements can alter not only the technical characteristics of a product, but also its symbolic or social value. And as the symbolic value of products changes, this in turn can alter consumer preferences. When technical efficiency improvements bring about an increased demand of energy that has been triggered by a change in consumer preferences, this can be termed a 'psychological rebound effect'. For example, demand for efficient products could be greater than for their conventional predecessors, because they are perceived as more environmentally friendly, and are less subject to social stigmatization. As micro-economic rebound research treats consumer preferences and elasticities as exogenous, and so far has not taken into account that technical efficiency improvements may trigger consumer preferences changes, elasticity-based calculations may also underestimate the scope of direct rebound effects.

Yet the assumptions of the models and methodologies chosen to a large extent determine the scope of rebound effects. This explains the polarized debate about the significance and actual scope of rebound effects. On the one side, 'rebound supporters'—among them mostly economists—tend to assume that consumers conform to the idea of '*homo oeconomicus*', for whom needs (or wishes) are insatiable, means ever scarce and therefore, the satisfaction of preferences is always determined by a cost-benefit analysis. Under these assumptions, any financial benefits from energy efficiency improvements will eventually be reinvested in increased demand, which means that rebound effects are generally large. On the other side, 'rebound skeptics' – among them often natural scientists and engineers —tend to assume that consumers prefer certain kinds of energy services, that these preferences remain more or less constant over time, and therefore, that they can either be satisfied with more efficient or less efficient technologies. In this view, energy efficiency improvements directly transfer into absolute reductions of energy use, and hence rebounds are considered small if not negligible. Both sides obviously operate with too broad-brushed assumptions about human behavior.

The exploration of consumer-side rebound effects on the basis of a more elaborate understanding of human behavior is still in its infancy. Girod and de Haan [31] are the first to suggest psychological rebound effects, which they term 'mental rebounds'. Otto, Kaiser, and Arnold [70] discuss psychological rebounds, but neither analyze how they evolve nor suggest a theoretical framework to do so. Peters et al. [32] suggest a theoretical framework to empirically analyzing psychological rebounds. In addition, Peters, Sonnberger, and Deuschle [33] have conducted focus groups on psychological rebounds with the general public in Germany. Santarius and Soland [34] are the first to move psychological and behavioral science theory forward into an approach to psychological rebound effects and a comprehensive rebound typology that integrates both economic and behavioral science explanations of potential rebound effects.

Santarius and Soland's psychological rebound theory, among others, also explains how technological efficiency improvements may alter consumer preferences in such a way that consumers actually reduce their energy service demand beyond the savings potential of the technology. Hence technological efficiency improvements may also generate 'negative rebound effects', which are beneficial to the goal of saving energy (see also[35]). However, such beneficial effects are due to specific conditions of individual behavior, such as strong environmental values and an intrinsic motivation to preserve energy. Hence beneficial effects should not be anticipated as a large-scale societal effect triggered by the introduction of more efficient technologies. At the same time, Santarius and Soland's psychological rebound theory explains how the purchase and usage of more efficient technologies may alter the attitude towards using technologies, and reduce feelings of responsibility when using them, in a way that generates rebound effects larger than anticipated by micro-economic calculations, which assume unchanged consumer preferences, ie., static elasticities. Empirical evidence on psychological rebound effects yet waits to be generated in order to decide whether elasticity-based, micro-economic calculations really underestimate the scope of direct consumer-side rebound effects—and if so, to what extent.

MESO-ECONOMIC REBOUND EFFECTS

Besides these consumer-related micro-economic rebounds, there are several producer-side and market-level rebound effects, which may be ascribed to the meso-economic level. Producer-side rebound effects have not been sufficiently investigated so far (for a beginning only, see [25], [23], [36], [37]). Yet the overall dimension of these rebound effects could be significant, since roughly two thirds of global energy is used in the production process, and

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32

only about one third during consumption. Although the level of the single firm can still be considered a micro-economic unit, historically micro-economic rebound research has only investigated consumer- or household-related rebounds. This article intends to start filling the research gap by investigating producer-side rebound effects that range from the level of the firm up to the level of a sector or market.

Reasons for Producer-side Rebounds

Five reasons can be identified why companies may demand more energy after an energy efficiency increase. First of all, investments in efficiency technologies necessarily increase demand for energy in order to produce such technologies. This energy use is termed ‘grey energy’ because it is ‘embodied’ in the efficiency technologies. The associated increased demand may be called an ‘embodied energy effect’ and can adequately be calculated on grounds of sector- and product-specific life-cycle assessments.

Two other reasons can be explained in terms of an income effect. They rest on the assumption that companies generate extra profit after having invested in an energy efficiency increase. For example, a firm can use the additional profit arising from an efficiency-boosting measure to expand production of the same product; this is equivalent to a direct rebound effect at the consumer level, yet here comes as an expansion of production. Alternatively, a company can use its increased profits to invest in new products and services; this is equivalent to an indirect rebound in the form of diversification of the product palette. In this case the production costs saved as a result of the improved efficiency of the production process for Good 1 are not used to produce more of Good 1 and sell it more cheaply; instead the money ‘cross-subsidizes’ production of another product, Good 2. This makes sense if, for example, the market for Good 1 is considered to be saturated, or if Good 2 is expected to yield a higher profit margin.

Another reason can be explained in terms of the substitution effect. In contrast to consumer-side rebounds that may rest on the substitution of end-use products, companies can substitute factor inputs in the production process. Most commonly, companies will make use of energy-efficiency increases to substitute labor through energy (and capital), e.g. through increased mechanization, automation, or digitalization. However, all economic inputs may partially be replaced by energy. For instance, in the case of steel production, the replacement of capital- and energy-intensive blast furnaces through electric arc furnaces not only increased energy but also capital productivity [11]. Likewise, other material resources, time, or space may be saved through increased energy use, as the example of just-in-time logistics shows, which has accelerated delivery times while reducing storage capacity and warehousing.

Finally, in addition to these effects as variants of the income and substitution effect on the production side, firms can also generate a rebound effect if expected cost savings for consumers lead them to invest in redesigning the original product, perhaps to improve its convenience. In this case companies are not acting in response to a production-side effect but in anticipation of a consumption-side income effect; more precisely, by redesigning the product, they are exploiting the anticipated income effect on the consumer side ex ante. In the past, for example, improvements in the efficiency of engine technology have seldom been used to produce cars that consume less fuel; instead, manufacturers have focused on marketing cars that have the same gas mileage but are heavier, faster and more powerful. The fuel consumption figures of the classic 1955 VW Beetle, which uses 7.5 liters of petrol per 100 kilometers, and the modern 2005 Beetle, which uses 7.1 liters over the same distance, are almost identical. But while the earlier model, which had a 30hp engine and reached a top speed of 110km/h, weighed just 730kg, the later one has a 75hp engine, a top speed of 160km/h and various additional features such as air conditioning; it weighs in at around 1,200kg [30].

Energy Price Effects

If a large number of individual actors in the market enhance their energy efficiency collectively, this may impact overall energy prices. The interaction of supply and demand ensures that lower prices for energy incentivize increased demand. In this manner, energy price effects of efficiency improvements can elicit a rebound effect. Energy price effects can arise in various markets, such as those for electricity (power), motor fuel (petrol, diesel), heating oil, coal and lignite, and gas. In the past the prices of the various energy carriers have often been linked, so that price effects in one market are transferred to the market for other energy carriers and then exert a combined effect at the economy-wide level.

As noted by Borenstein [37], the quantity of energy price effects depend on elasticities of supply and demand, with inelastic demand or elastic supply resulting in less rebound effects and elastic demand or inelastic supply resulting in larger rebounds. Usually, supply has been rather inelastic in oil markets while more elastic in gas, coal

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32

and electricity markets. Therefore, high energy price effects are particularly probable in oil markets as well as secondary markets which largely depend on oil prices but face high demand elasticities from consumers.

The energy price effect tends in the same direction as the income effect at individual level, but a clear distinction should be made between the two. In the case of the income effect, rebound effects occur because the initial reduction in people's consumption of an energy resource that results from an efficiency improvement reduces the cost of energy to individuals and hence creates an incentive to express more demand for energy — even if the price of energy remains unchanged. The energy price effect creates an additional incentive to increase demand if the reduced price of an energy resource reduces the cost of a particular level of energy consumption. For example, the income effect means that petrol costs fall by 50% when a driver switches from a car that runs, say, 20 miles per gallon (MPG) to one that runs 40 MPG. This releases money for increased energy use — whether for additional journeys or for other energy-consuming goods and services. Moreover, an energy price effect can also occur if there is broad-scale replacement of 20 MPG vehicles by 40 MPG ones and this leads — at least in theory — to a halving of the price of petrol. However, because there is demand for petrol not only in the sector that has become more efficient but also in other sectors, and because, moreover, the prices of different energy resources are at least partially linked, the price of petrol is in reality unlikely to be halved, but it will fall to some degree.

There are two ways in which this general fall in price can result in increased demand. Firstly, the lower price of one form of energy can trigger rebound effects by stimulating demand from other sectors. For example, a fall in the price of petrol can result in increased demand for other petrol-using products, which are now cheaper to operate; for instance, stock-keeping may be increasingly replaced by transport-intensive just-in-time logistics. And secondly, the energy price effect can amplify the direct rebound effect on the consumer side: consumers may realize a net income effect both through lower costs when running a more efficient device, as well as through lower prices they pay for the still remaining energy demand.

Both Turner et al. [38] and Sorrell [24] use the term 'composition effect' to describe this substitution effect — that is, the way in which the energy price effect influences indirect rebound effects. Reduced energy prices can indeed alter the composition of the portfolio of goods and services in a country's economy. Just as the energy price effect tends in the same direction as the income effect, the composition effect amplifies the impact of the substitution effect described above. But in contrast to the substitution effect, which can also occur in the absence of any income effect, the composition effect is ultimately only a variant of the energy price effect: there can be no composition effect without an energy price effect. Either the composition of the economy changes simply as a result of the sum of all micro-economic substitution effects, or the interaction of micro-economic income and substitution effects gives rise to an energy price effect, one of the impacts of which may be to alter the composition of the economy's portfolio of goods.

'Guesstimates' of Producer-side Rebound Effects

The state of empirical research on meso-economic rebound effects is quite meager. Two econometric analyses by Bentzen [39] and Saunders [40] are the only studies that explicitly calculate production-side rebound effects in the USA. Using time series data covering the period 1949 to 1999, Bentzen estimates a 24% rebound effect for the US manufacturing sector on the whole [39]. Saunders disaggregates US manufacturing into 30 sectors. Using records from 1960 to 2005 for 30 sectors of the US economy, he simulates the rebound effects that would have occurred if there had been no improvements in efficiency after 1980. Rebound effects calculated for the different sectors average 120% between 1981 and 1990 and 60% between 1991 and 2000. However, a few sectors, e.g. electricity production, significantly peak out; leaving these aside, rebounds range between 30-60% for most sectors analyzed [40].

Further disaggregation of economy-wide and sector-level data into research for certain branches or even individual firms are deeply needed to understand better, and more accurately calculate the scope of, producer-side rebounds. Commercial transportation is the only (sub-)sector where producer-side rebounds have been researched more profoundly, yet still with significantly diverging results. Empirical findings of five studies place the scope of rebound effects in freight transportation between 17% and 80% (see [41], [42], [43], [44], [45]). Note that these studies quantify the scope of producer-side rebounds in transportation significantly higher than the average level of consumer-side rebounds from private transportation, which are estimated around 10% for the USA [46], [47].

MACRO-ECONOMIC REBOUND EFFECTS

While consumer-side rebound effects were the subject of a fundamental debate in the 1980s (e.g. Kazzhoum vs. Lovins [18], [12], Brookes vs. Grubb [9], [48], etc.), today the general occurrence of these effects is largely undisputed. However, their quantitative magnitude is still controversial. In contrast, macro-economic rebound

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32

TABLE 2. Overview of econometric calculations of macro-economic rebound effects

Reference	Country / Region	Range of results
Allan et al. (2006) [60]	Great Britain (GB)	37%
Barker et al. (2007) [61]	GB	26%
Barker et al. (2009) [59]	World (without internat. bunkers)	51%
Dufournaud et al. (1994) [62]	Sudan	47 – 77%
Glomsrod/Taoyuan (2005) [63]	China	> 100%
Grepperud/Rasmussen (2004) [64]	Norway	> 100%
Guerra/Sancho (2010) [52]	Spain	40% – 100%
Semboja (1994) [65]	Kenya	> 100%
Turner et al. (2009) [38]	GB and Scottland	90% – >100%
Vikström (2008) [66]	Sweden	50 – 60%
Washida (2004) [67]	Japan	53%

effects—understood as that part of overall economic growth which has been stimulated by improvements in the energy productivity of the economy—is still called into question, probably because its functioning is still insufficiently understood.

It was Jevons in 1865 [49] who first discovered the link between energy efficiency improvements and overall economic growth (see also [50]). Since the late 1970s, this relation has been reformulated by Brookes ([8], [9], etc.) and was mainly theorized by Saunders (e.g. [10], [11]). In recent years, the debate on macro-economic rebound effects has been mainly structured by Sorrell and others (e.g. [24];[51]; [21]).

The Productive Power of Energy

In economic terms, technological efficiency improvements can be understood as the substitution of energy through capital (and knowledge). For example, the production of low energy homes usually is more costly than of conventional homes, but the former require less energy for heating the same amount of square feet than the latter; hence fuel demand can be substituted through capital investments. On the macro-economic level, the question arises: To what extent do the production factors of capital and energy relate like 'substitutes', so that capital actually replaces energy? Or do energy and capital rather relate as 'complements', so that increased investments in, or spending of capital bring about an increased demand for energy?

Saunders [11] as well as Birol and Keppler [19] postulate the theorem: the greater the elasticity of substitution between the production factors energy and capital—or more accurately: the energy price elasticity of substitution of energy for capital—the greater the rebound effects (see this also econometrically in [52]). From this theorem, one could derive a somewhat counter-intuitive conclusion: The more energy can be replaced by capital—and that is what is actually going to happen when investments in energy efficiency replace demand for energy carriers across all sectors of the economy—the larger will macro-economic rebound effects potentially be. However, Howard [53] argues that the elasticity of substitution between energy and capital usually be limited ($0<e<1$) rather than high ($e>1$). According to him, therefore, backfire is rather unlikely. Yet regrettably, the empirical literature is far from uniform on this question and cannot even agree on a range of the elasticity in question. After several decades of research, no reliable figures exist that could clarify this issue empirically (see [51], p. 51).

Furthermore, it seems reductionist to isolate the discussion of substitution elasticities from the discussion of output elasticities. For the energy elasticity of substitution partly depends on how strongly an improvement in the

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32

productivity of the production of certain goods or services impacts the overall demand for those goods and services —and hence, the overall level of production in the economy. And in turn, the sum of overall economic growth in production will influence the overall demand for energy services. This allows for another theorem to be deduced: The greater the output elasticities of the production factor of energy, the greater are the potential rebound effects. However again, different estimates of the actual scope of the production factor of energy can be found in the literature. In the tradition of the early macro-economic growth theorists Solow and Swan, most neoclassical economists assume that the output elasticities of all factors of production correspond to their factor cost shares of gross domestic product [54]. Since these factor cost shares in developed countries usually amount to ranges around 50%-65% for labor, 5%-10% for energy, and 30%-40% for capital, energy as a production factor is usually awarded a low output elasticity (see also [55]). Under neoclassical assumptions, energy efficiency improvements will generate rather small macro-economic rebound effects.

On the other hand, ecological economists often assume that energy as a production factor has a much higher output elasticity, which cannot be attributed to its low cost share of GDP. According to the laws of thermodynamics, ecological economists attribute energy a key role in the growth process of industrial economies (e.g. [56]; [55]). Based on a production function that conforms to this premise, Lindenberger and Kümmel [57] calculate output elasticities in the USA (Germany) for capital to about 51% (38%), for labor to 14% (15%), and for energy to about 35% (38%), respectively. Given ecological economics' assumptions and data, improvements in energy efficiency will significantly stimulate economic growth and cause high rebound effects.

Economic Growth along the Energy-Capital Nexus

It is beyond the scope of this paper to reconcile this almost 'ideological struggle' between neoclassical and ecological economics. Yet note that the impacts of energy efficiency improvements on overall economic growth are not only determined by the output elasticity of energy, but also by the output elasticity of capital. Namely, how much do increased capital investments into more efficient technology improve the productivity of capital as a production factor, and thus spur growth through both enhanced capital and energy productivity? For the question of macro-economic rebound effects, it is therefore somewhat less important whether the perspective of neoclassical or of ecological economics is actually right. The output elasticity of energy efficiency improvements must be understood as a conglomerate of the production elasticities of both energy and capital. And as the above figures show, there are far fewer divergences on estimating the output elasticity of capital through either an ecological economics or a neoclassical lens; the productive power of capital is generally considered to be significant.

As the discussion shows, economic theory is far from providing a robust framework for estimating the magnitude of macro-economic rebound effects. Several profound research questions need to be tackled, inter alia: how does the output elasticity of capital and energy evolve when investment in energy efficiency increases? What characterizes the interrelationship between the evolving output elasticities of capital and energy? And how do they eventually affect the elasticity of substitution between energy and capital? The answers to these questions largely determine whether moderate or high macro-economic rebound effects are to be expected.

Range of Macro-Economic Rebound Effects

Given these profound insecurities, results from econometric modeling that tries to quantify macro-economic rebound effects must be treated with great caution. Currently, 11 model calculations for macro-economic rebound effect are available (see Table 2). The results of these studies vary between 26% and >100% macro-economic rebound effects, with four studies calculating backfire. Yet these results are barely comparable, because underlying model assumptions as well as national data significantly vary (for details on the assumptions and results of several of the studies, see [58]). The study by Barker et al. [59] calculates rebound effects at world level at 51%; the same model computes rebounds for the UK at only 26%, the lowest result of all studies. Still, note that only macro-economic rebounds have been calculated. So even to the low measure of 26%, micro-economic rebounds in the range of 10-30% (see above) must still be added to arrive at the economy-wide sum of all potential rebounds.

In addition, two arguments suggest that econometric calculations rather under- than overestimate the actual dimension of macroeconomic rebound effects. First, all models follow neoclassical assumptions that elasticities correspond to factor cost shares. With ecological economics' assumptions, macro-economic rebound effects were probably considerably larger. Second, all econometric studies have only modeled the effect of pure 'energy efficiency improvements'. However, and as elaborated above, energy efficiency improvements will also lead to productivity increases in capital and labor, which is likely to potentiate the rebound effects. Such "cross factor

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32

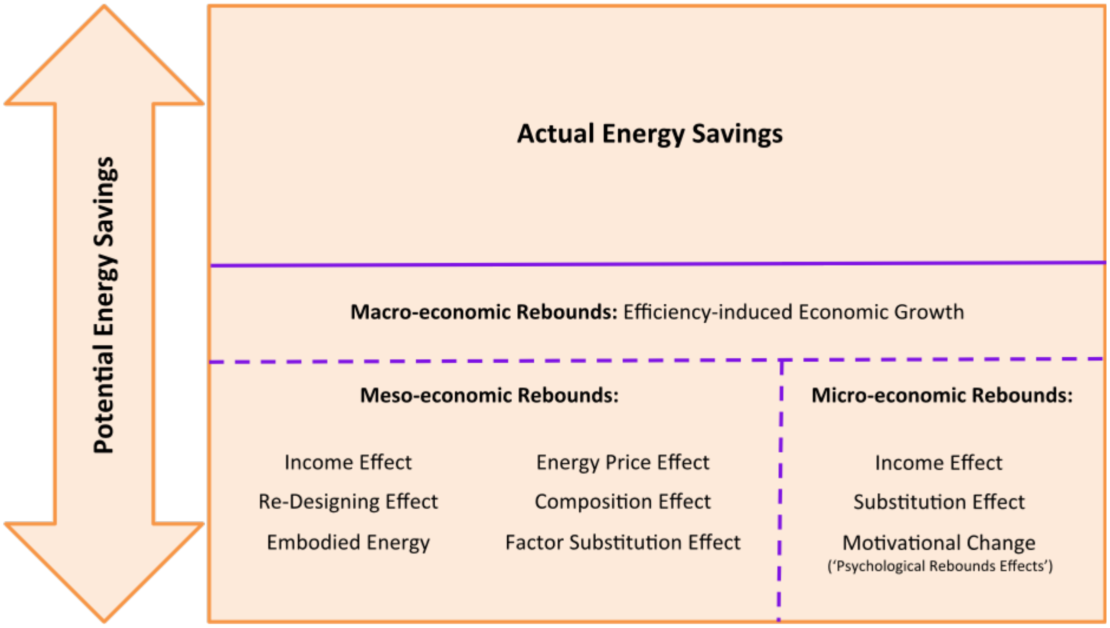

FIGURE 1. Overview of potential rebound effects at micro-, meso- and macro-level. Source: Author's own design, adapted from [24], p. 4

rebound effects" [30] so far have neither been sufficiently discussed in economic theory nor have they been included in the quantitative analysis quoted above.

CONCLUSIONS

This article investigated rebound effects as the causal relationship between technological energy efficiency improvements, human behavior, industrial production, and economic growth as key challenges to the endeavor of reducing energy demand and greenhouse gas emissions to sustainable levels. It set out by reviewing and summarizing the main findings of micro-economic rebound research and outlined remaining deficiencies. The article argued for expanded research on consumer-side rebounds beyond economics into behavioral and social sciences, so as to take note of motivational changes triggered by technological efficiency improvements. Secondly, the article proposed in-depth research at the meso-economic level to cover producer-side and energy price-related rebound effects. Notwithstanding the limited state of research on these effects, the theoretical discussion in this article suggests that the scope of production-side rebound effects is likely to be greater than that of direct consumer-side direct rebound effects. Thirdly, the article has disclosed major research gaps in the economic debate on macro-economic rebound effects. At the same time arguments have been brought forward why existing econometric modeling so far might rather under- than overestimate the magnitude of macro-economic rebound effects.

Given weak empirical evidence and heterogeneous assumptions namely for meso- and macro-economic rebounds, it is not possible to pronounce on a number for the total sum of all rebounds at the economy-wide level. This sum may be located between 40% and 60% with some probability (see also [68]), but can well deviate even from that range. For the hurried reader and policy-maker, it is therefore no more than a rough "rule of thumb" that the magnitude of all economy-wide rebound effects, in the long term and on gross average, may cut the technical savings potential of an across-the-board energy efficiency improvement of the economy in a half (see also [68], p. 353).

In any case, even the range of rebounds given suggests that a sufficient absolute reduction of energy service demand in modern societies can hardly be achieved with an efficiency strategy alone—or if so, only at significantly higher costs than envisioned by those scenarios that assume realization of full technical savings potentials (see quotes above). Sustainability politics that aims at significantly reducing greenhouse gas emissions, and intends to transition to renewable energy sources, is therefore well-advised to take note of rebound phenomena, and to develop policies and measures to confine these effects. Among others, measures could include capping absolute energy and resource consumption (e.g. through national energy caps, up-stream emissions trading schemes, or the like) as well as consumer-oriented policies that combine energy efficiency with actual energy conservation (i.e., 'sufficiency').

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32

ACKNOWLEDGEMENT

The foregoing draws substantially from the author's translation of his original publication in German, *Gaia* 23(2), 109-117 (Oekom; Munich; 2014), with permission of the publishers.

REFERENCES

1. IPCC. 2014: Climate Change 2014: Mitigation of Climate Change. Online at http://www.ipcc.ch/report/ar5/wg3/.
2. IPCC. 2007. Climate Change 2007: Synthesis Report. Cambridge.
3. McKinsey & Company. 2010. Impact of the financial crisis on carbon economics. Version 2.1 of the Global Greenhouse Gas Abatement Cost Curve. Download at http://www.mckinsey.com/client_service/sustainability/latest_thinking/greenhouse_gas_abatement_cost_curves
4. WWF. 2011. The Energy-Report. 100% Renewables by 2050. Gland.
5. European Climate Foundation (2010): Roadmap 2050. A Practical Guide to a prosperous low-carbon Europe. Brussels/ Berlin.
6. EREC. 2010. Re-Thinking 2050. A 100% Renewable Energy Vision for the European Union. Brussels.
7. Ayres, R. U., B. Warr. 2009. The economic growth engine: How energy and work drive material prosperity. Cheltenham: Edward Elgar.
8. Brookes, L. 1978. Energy policy, the energy price fallacy and the role of nuclear energy in the UK. Energy Policy 6: 94–106.
9. Brookes, L. 1990. The greenhouse effect: The fallacies in the energy efficient solution. Energy Policy 18: 199–201.
10. Saunders, H. D. 1992. The Khazzoom-Brookes postulate and neoclassical growth. The Energy Journal 13: 131–148.
11. Saunders, H. D. 2000. A view from the macro side: Rebound, backfire, and Khazzoom-Brookes. Energy Policy 28: 439–449.
12. Lovins, A. B. 1988. Energy saving from the adoption of more efficient appliances: Another view. The Energy Journal 9: 155–162.
13. Lovins, A. B. 2011. Re: The efficiency dilemma: A letter in response to David Owen's article. The New Yorker, 17.01.2011.
14. Schipper, L., M. Grubb. 2000. On the rebound? Feedback between energy intensities and energy uses in IEA countries. Energy Policy 28: 367–388.
15. Goldstein, D.B., Martinez, S., Roy, R. 2011. Are There Rebound Effects from Energy Efficiency? – An Analysis of Empirical Data, Internal Consistency, and Solutions. EnergyPolicy.com, 08 May, 2011. Online at: http://www.electricitypolicy.com/articles/3138-are-there-rebound-effects-from-energy-efficiency-an-analysis-of-empirical-data-internal-consistency-and-solutions.
16. Nadel, S. 2012. The Rebound Effect: Large or Small? An ACEEE White Paper. Online at: http://aceee.org/files/pdf/white-paper/rebound-large-and-small.pdf.
17. Khazzoom, J. D. 1980. Economic implications for mandated efficiency in standards for household appliances. The Energy Journal 1: 21–40.
18. Berkhout, P. H. G., J. C. Muskens, J. W. Velthuijsen. 2000. Defining the rebound effect. Energy Policy 28: 425–432.
18. Khazzoom, J. D. 1987. Energy saving resulting from the adoption of more efficient appliances. The Energy Journal 8: 85–89.
19. Birol, F., J. H. Keppler. 2000. Prices, technology development and the rebound effect. Energy Policy 28: 457–469.
20. Binswanger, M. 2001. Technological progress and sustainable development: What about the rebound effect? Ecological Economics 36: 119–132.
21. Maxwell, D. et al. 2011. Addressing the rebound effect: A report for the European Commission DG Environment. Brüssel: Europäische Kommission.
21. Sorrell, S. 2009. Jevons' paradox revisited: The evidence for backfire from improved energy efficiency. Energy Policy 37: 1456–1469.
22. Madlener, R., B. Alcott. 2011. Herausforderungen für eine technisch-ökonomische Entkoppelung von Naturverbrauch und Wirtschaftswachstum unter besonderer Berücksichtigung der Systematisierung von Rebound-Effekten und Problemverschiebungen. Berlin: Enquete-Kommission „Wachstum, Wohlstand, Lebensqualität" des Deutschen Bundestages.
23. Jenkins, J., T. Nordhaus, M. Shellenberger. 2011. Energy emergence. Rebound & backfire as emergent phenomena. Oakland: Breakthrough Institute.
24. Sorrell, S. 2007. The rebound effect: An assessment of the evidence for economy-wide energy savings from improved energy efficiency. London: UK Energy Research Centre.
25. Greening, L., D. L. Greene. 1998. Energy use, technical efficiency, and the rebound effect: A review of the literature. Oak Ridge: Oak Ridge National Laboratory.
25. Herring, H. 2006. Energy efficiency - a critical view. Energy 31: 10–20.
26. Azevedo, I.L., Sonnberger, M., Thomas, B., Morgan, G., Renn, Ortwin O. 2012. The Need to Account for Consumer Behaviour in order to Develop Robust Energy Efficiency Policies. A review of the literature on the rebound effect in energy efficiency and report from expert workshop. Stuttgart: University of Stuttgart.
26. Frondel, M., C. Vance. 2011. Re-identifying the rebound: What about asymmetry? Bochum: Ruhr-Universität Bochum (Ruhr Economic Papers 276).
27. Boardman, B., G. Milne. 2000. Making cold homes warmer: The effect of energy efficiency improvements in low-income homes. Energy Policy 28: 411–424.
28. Sorrell, S., J. Dimitropoulos. 2008. The rebound effect: Microeconomic definitions, limitations and extensions. Ecological Economics 65: 636–649.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32

29. Jalas, M. 2002. A time use perspective on the materials intensity of consumption. Ecological Economics 41: 109–123.
30. Santarius, T. 2012. Green Growth Unraveled. How Rebound Effects Baffle Sustainability Targets When the Economy Keeps Growing. Berlin/Washington: Heinrich Boell Foundation.
31. Girod, B., P. de Haan. 2009. Mental rebound. Zürich: Eidgenössische Technische Hochschule (Rebound Research Report 3).
32. Peters, A., M. Sonnberger, E. Dütschke, J. Deuschle. 2012. Theoretical perspective on rebound effects from a social science point of view. Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung (Working Paper Sustainability and Innovation S 2).
33. Peters, A., M. Sonnberger, J. Deuschle. 2012b. Rebound-Effekte aus sozialwissenschaftlicher Perspektive – Ergebnisse aus Fokusgruppen im Rahmen des REBOUND-Projektes. Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung (Working Paper Sustainability and Innovation S 5).
34. Santarius, T., Soland, M. (forthcoming): Technological Efficiency Improvements Change Consumer Preferences: Towards a Psychological Theory of Rebound Effects. Unpublished manuscript.
35. Santarius, T. 2014. Der Rebound-Effekt: ein blinder Fleck der sozial-ökologischen Gesellschaftstransformation. GAIA 23/2: 109 -117.
36. Michaels, R. 2012: Energy efficiency and climate policy: The rebound dilemma. A report by the Institute for Energy Research. Online at: http://www.instituteforenergyresearch.org/efficiency-rebound-dilemma/
37. Borenstein, S. 2013. A microeconomic framework for evaluating energy efficiency rebound and some implications. Berkeley: Energy Institute at Haas (E2e Working Paper 005).
38. Turner, K., N. Hanley, J. de Fence. 2009. Do productivity improvements move us along the Environmental Kuznets Curve? Sterling: University of Sterling Management School (Stirling Economics Discussion Paper 2).
39. Bentzen, J. 2004. Estimating the rebound effect in US manufacturing energy consumption. Energy Economics 26(1): 123-134.
40. Saunders, H. D. 2013. Historical evidence for energy consumption rebound in 30 US sectors and a toolkit for rebound analysis. Technological Forecasting and Social Change 80: 1317–1330.
41. Gately, D. 1990. The U.S. demand for highway travel and motor fuel. The Energy Journal 11: 59–74.
42. Graham, D., S. Glaister. 2002. Review of income and price elasticities of demand for road traffic. London: Centre for Transport Studies, Imperial College of Science, Technology and Medicine.
43. Anson, S., K. Turner. 2009. Rebound and disinvestment effects in oil consumption and supply resulting from an increase in energy efficiency in the Scottish commercial transport sector. Glasgow: University of Strathclyde (SIRE Discussion Papers in Economics 05).
44. Matos, F. J. F., F. J. F. Silva. 2011. The rebound effect on road freight transport: Empirical evidence from Portugal. Energy Policy 39: 2833–2841.
45. De Borgera, B., Mulalic, I. 2012. The determinants of fuel use in the trucking industry—volume, fleet characteristics and the rebound effect. Transport Policy 24: 284-295.
46. Small, K.A., VanDender, K. 2007. Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect. The Energy Journal 28(1): 25-52.
47. Sorrell, S., J. Dimitropoulos, M. Sommerville. 2009. Empirical estimates of the direct rebound effect: A review. Energy Policy 37: 1356–1371.
48. Grubb, M. J. 1990. Energy energy efficiency and economic fallacies. Energy Policy 18: 783–785.
49. Jevons, W. S. 1906. The coal question: An inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines. 3., durchgesehene Auflage der Ausgabe von 1865. London: Macmillan and Co.
50. Alcott, B. 2005. Jevons' Paradox. Ecological Economics 54: 9–21.
51. Broadstock, D. C., L. Hunt, S. Sorrell. 2007. UKERC review of evidence for the rebound effect. Technical report 3: Elasticity of substitution studies. London: UK Energy Research Centre.
52. Guerra, A., Sancho, F. 2010. Rethinking economy-wide rebound measures: An unbiased proposal. Energy Policy 38: 6684-6694.
53. Howarth, R. B. 1997. Energy efficiency and economic growth. Contemporary Economic Policy XV: 1–9. — text says Howard, this says Howarth
54. Solow, R. M. 1956. A contribution to the theory of economic growth. The Quarterly Journal of Economics 70: 65–94.
55. Kümmel, R. 2011. The second law of economics: Energy, entropy, and the origins of wealth. New York u. a.: Springer.
56. Stern, D. I., C. J. Cleveland. 2004. Energy and economic growth. Troy: Rensselaer Polytechnic Institute (Rensselaer Working Papers in Economics 0410).
57. Lindenberger, D., R. Kümmel. 2011. Energy and the state of nations. Energy 36: 6010–6018.
58. Allan, G., M. Gilmartin, P. McGregor, K. Swales, K. Turner. 2007. UKERC Review of evidence for the rebound effect. Technical report 4: Computable general equilibrium modelling studies. London: UK Energy Research Centre.
59. Barker, T., A. Dagoumas, J. Rubin. 2009. The macroeconomic rebound effect and the world economy. Energy Efficiency 2: 411–427.
60. Allan, G.J., Hanley, N.D., McGregor, P.G., Swales, J.K., Turner, K.R. 2006. The macroeconomic rebound effect and the UK economy. Final report to the Department of Environment Food and Rural Affairs. Strathclyde: University of Strathclyde.
61. Barker, T., Ekins, P., Foxon, T.J. 2007. The macro-economic rebound effect and the UK economy. Energy Policy 35: 4935-4946.
62. Dufournaud, C.M., Quinn, J.T., Harrington, J.J. 1994. An applied general equilibrium (AGE) analysis of a policy designed to reduce the household consumption of wood in the Sudan. Resource and Energy Economics 16(1): 67-90.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32

63. Glomsrød, S., Taojuan, W. 2005. Coal cleaning: a viable strategy for reduced carbon emissions and improved environment in China? Energy Policy 33(4): 525-542.
64. Grepperud, S., Rasmussen, I. 2004. A general equilibrium assessment of rebound effects. Energy Economics 26(2): 261-82.
65. Semboja, Haji Hatibu Haji 1994: The effects of an increase in energy efficiency on the Kenyan economy. Energy Policy 22(3): 217-225.
66. Vikström, P. 2008. Energy efficiency and energy demand: a historical CGE investigation on the rebound effect in the Swedish economy 1957. Umeå Papers in Economic History Nr. 35. Department of Economic History. Umea: Umea University.
67. Washida, T. 2004. Economy-wide model of rebound effect for environmental policy. Paper presented at International Workshop on Sustainable Consumption, University of Leeds, March 5th-6th 2004. Download: http://eco.genv.sophia.ac.jp/paper/leeds/LeedsPaper.pdf
68. Gillingham, K., M. J. Kotchen, D. S. Rapson, G. Wagner. 2013. The rebound effect is overplayed. Nature 493: 475–476.
69. SRU. 2011. Wege zur 100 % erneuerbaren Energieversorgung. Sondergutachten. Berlin: Erich Schmidt.
70. Otto, S., F.G. Kaiser, O. Arnold. 2014. The critical challenge of climate change for psychology: Preventing rebound and promoting more individual irrationality. European Psychologist 19: 96-106.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 79.206.218.8 On: Fri, 03 Apr 2015 08:47:32