Consumption and the Rebound Effect

An Industrial Ecology Perspective

Edgar G. Hertwich

Summary

Measures taken to protect the environment often have other, unintended effects on society. One concern is that changed behavior may offset part of the environmental gain, something that has variously been labeled "take-back" or "rebound." In energy economics, the rebound effect encompasses both the behavioral and systems responses to cost reductions of energy services as a result of energy efficiency measures. From an industrial ecology perspective, we are concerned about more than just energy use. Any given efficiency measure has several types of environmental impacts. Changes in the various impact indicators are not necessarily in the same direction. Both co-benefits and negative side effects of measures directed to solve one type of problem have been identified. Environment is often a free input, so that a price-based rebound effect is not expected, but other indirect effects not connected to the price, such as spillover of environmental behavior, also occur. If the costs and impact of products that are already environmentally friendly are reduced, the "rebound" can be in the opposite, desired direction. Furthermore, I identify technical spillover effects. Hence a number of related effects, often producing positive results, are not as well understood. Household environmental impact assessments and eco-efficiency assessments take into account the rebound effect, but they do not necessarily take into account these other effects. The analysis hence indicates that the current focus on the rebound effect is too narrow and needs to be extended to cover co-benefits, negative side effects, and spillover effects.

Address correspondence to:
Prof. Edgar Hertwich
Industrial Ecology Program
Norwegian University of Science and Technology
NO-7491 Trondheim, Norway
<edgar.hertwich@ntnu.no>

Introduction

In discussions of sustainable consumption, the rebound effect is often mentioned as something requiring serious attention. In fact, research on sustainable consumption and, hence, on behavior is sometimes justified with reference to the rebound effect. In these discussions, the rebound effect refers to a behavioral or other systemic response to a measure taken to reduce environmental impacts that offsets the effect of the measure. As a result of this secondary effect, the environmental benefits of eco-efficiency measures are lower than anticipated (rebound) or even negative (backfire). Given its potential importance to sustainable consumption *and* production, a clear understanding of the rebound effect is required. In this article, I investigate the rebound effect from an industrial ecology perspective in order to evaluate its significance for and assess its relevance to sustainable consumption.

I start the investigation with a review of research on rebound effects in energy economics, because the concept originates in this field. In fact, several effects are grouped under the term rebound effect, and a classification of these effects is indeed useful. I then investigate the rebound effect in relation to concepts discussed in industrial ecology (IE). I point to a number of additional effects, which are also secondary effects of a primary policy measure. These effects are not necessarily negative. On the contrary, co-benefits and spillover effects can be of substantial interest to the policy maker. A graphical presentation of eco-efficiency on a plane of value and environmental impacts can be used to capture certain rebound effects. This representation shows that, indeed, win-win efficiency measures can lead to positive side effects.[1] Our further investigation of rebound-type effects in IE shows that some of these issues have been addressed in previous attempts to model the consequences of our decisions. Further, I discuss the relevance of the rebound effect to sustainable consumption. I point to the fact that the income effect identified in energy economics has *always* been addressed in household environmental impact (HEI) assessments, but other effects have not. Finally, I discuss the relevance of the reasoning that underlies the rebound effect to sustainable consumption and its implications for further research and policy development.

The Rebound Effect in Energy Economics

In the aftermath of the oil price increases in the 1970s, energy policy shifted from being purely focused on supply-side considerations to include energy demand. Energy efficiency measures, such as technology standards and home weatherization campaigns, were introduced to energy policy. Khazzoom (1980), however, questioned the notion that improved energy efficiency necessarily leads to reductions in energy demand. Energy efficiency reduces the marginal cost of energy services, that is, of providing a comfortable room temperature, lighting a room, or getting from point A to point B.[2] Energy efficiency hence leads to an increased demand for those services. The reduction in energy demand will hence be less than proportional to the reduction in energy use per unit service. Brookes (1978; 2000) argued that energy efficiency will lead to economic growth, which in turn can lead to a *net increase* in energy demand. Saunders (1992) presented a formal economic model for this hypothesis. These articles triggered a discussion that addressed both the mechanisms and the magnitude of this rebound effect (Henly et al. 1988; Lovins 1988; Brookes 1990; Grubb 1990).[3]

With regard to the magnitude of the effect, analysts distinguish a weak rebound effect (efficiency measures are not as effective as expected), a strong rebound effect (most of the expected savings do not materialize), and a backfire effect (the efficiency measure leads to increased energy demand). With regard to the economic mechanism, Greening and colleagues (2000) distinguish between the following effects:

1. The *substitution effect:* the increase in demand for an energy service that becomes cheaper as a result of the increase in energy efficiency because of a reallocation of income to this service.
2. The *income effect:* the increase in available income as a result of the reduced price of the energy service, which leads to other energy-consuming purchases.

3. *Secondary effects* (input-output effects): A technical energy efficiency measure also reduces the cost of energy services to industry, which leads to price reductions of goods and services and hence to increased demand in these goods and services and therefore in the energy service.

4. *Market-clearing price and quantity adjustments* (especially in fuel markets) or *economy-wide effects*: If energy efficiency reduces the demand for fuel, the fuel price will go down. As a result of the fuel price reduction, more fuel will be bought.

5. *Transformational effects*: Changes in technology have the potential to change consumers' preferences, alter social institutions, and rearrange the organization of production.

The first two effects, sometimes also called direct rebound effects, are *micro* effects that play themselves out on the level of the single household. The last three effects are *macro* effects that result from the interaction between different actors, both producers and consumers, in the economy.

Direct Rebound Effects

Khazzoom's (1980) rebound model looks only at a single service and measures the increase in quantity demanded of this service due to a decrease in its price. Such a model hence combines substitution and income effects but does not consider their impact on other services and products consumed. Lovins (1988) has argued that the income effect, which in general is lower in magnitude, is likely to dominate the substitution effect. Binswanger (2001) investigates this issue in a situation with two services and shows that the income effect can indeed even lead to reductions in energy use, if the energy-intensive good is an inferior good (i.e., demand for the good falls as a person's income rises).

Most empirical studies focus on the substitution and income effects, because the other effects are difficult to isolate. Greening and colleagues (2000) present a comprehensive 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 than 30% (space heating, lighting, automotive transport). The survey contains a careful consideration of empirical methods and indicates that early studies were biased. 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%. Most of the studies reviewed by Binswanger (2001) also point to rebound effects of less than 25%; only a study by Khazzoom (1986) on electrically heated homes in Sacramento, California in the USA shows a rebound effect of as high as 65%, whereas a study on road transport in Germany and Italy shows rebounds between 30 and 50% (Walker and Wirl 1993).

According to Binswanger, the problem with empirical estimates of the rebound effect is that the rebound effect is not directly observed; instead it is inferred from price elasticities of service demand, that is, the degree to which the demand for energy services is responsive to price. Such a calculation is based on strong assumptions: (1) A single energy service exists. (2) The energy cost is only the marginal cost of providing the service. (3) Energy efficiency investments are reversible. In addition, estimates of price elasticities cannot be derived in situations of constant energy prices.

Haas and Schipper (1998) show that energy-price elasticities are not constant with time and tend to be higher for periods with rising energy prices than for periods with falling energy prices. This means that, as energy prices increase, people invest in energy-efficient technology. When the energy price goes down again, the investment stays in place, and the energy demand does not increase as much as one would expect based on the price elasticity measured during the period of rising energy prices.

In a study of heating energy use in Austria Haas and Biermayr (2000) illustrate different approaches measuring the direct rebound effect. They use both cross-sectional and longitudinal statistical analysis, taking into account the asymmetry of the price elasticity. They also include an intervention study looking at the change of energy use in apartment buildings with a building retrofit. They find a 30% rebound of heating energy in all cases. Bentzen (2004) also systematically explores the asymmetry in the energy price elasticity in a study of manufacturing energy use

in the United States. He finds a direct rebound effect of 24% when looking only at periods of decreasing energy price. This is about half as much as the estimated effect using both periods of decreasing and increasing price. Consumers would, presumably, react in a similar manner to cost reductions due to efficiency increases as they do to cost reductions due to changes in energy price. An increase in efficiency would hence lead to a lower rebound than measurements of the price elasticity during periods of increasing energy demand would suggest.

From the studies reviewed, it seems that a strong rebound occurs in situations where the energy service consumption is cost constrained. An example is space heating: poor households heat only a few selected rooms and only during periods when they are occupied. Insulation allows households to heat more rooms, continuously. The introduction of central heating, which is also more efficient, has a similar effect. A strong rebound effect is therefore most likely to be detected in poorer economies and lower income groups (Roy 2000).

Interestingly, the discussion of the rebound effect in energy economics focuses on reductions in the price of energy services as a result of energy efficiency measures and the effect this has on demand. As Binswanger (2001) has pointed out, the cost of an energy service also includes the time spent by the consumer. This has not been included in the traditional rebound theories, in spite of the fact that the substitution between time and money is a central concern of consumer economics. Discussions of a *time rebound* have recently appeared in the sustainable consumption literature (Jalas 2002, 2005; Perrels 2002; Hofstetter and Madjar 2003). The time rebound effect results when the time saving due to technical progress leads to increased consumption. For example, transportation research has shown that faster transport implies that people expand their radius of action but keep their total travel time constant (Goodwin 1978).

Indirect Rebound Effects

Although Khazzoom and Brookes are usually cited in the same sentence, it seems that the argument by Brookes is much more a macro-argument that addresses secondary and higher-order effects, effects on growth and hence production rather than on individual consumption habits. Secondary effects imply that energy efficiency leads to growth, from the perspective of economic policy makers not an undesired result. Brookes (2000) argues that energy productivity will always tend to be pursued and employed in ways that lead to raising multifactor productivity growth more rapidly than energy productivity growth. This implies that economic output is the aim of economic activity, not energy efficiency. Actions will therefore be guided by their effect on output, and this direct effect is likely to be stronger than the indirect effect this has on energy efficiency. Writing in 1865 about the danger of Britain running out of coal, Jevons argued, "Nor will the economical use of coal reduce its consumption. On the contrary economy renders the employment of coal more profitable and thus the present demand for coal increased. . . " (Brookes 2000, p. 359). The argument is that the higher productivity of an energy source makes the source more accessible for various applications. This has certainly happened with the introduction of electricity as an energy carrier. Responding to Brookes, Grubb (1990) argues that history is a poor guide to what will happen in the future. Although activities in the past used to be constrained by the availability of energy, this is not the binding constraint any more. In addition, he argues that there is a fundamental difference between naturally occurring and policy-driven efficiency improvements. Policy reduces transaction costs and addresses market failures that are responsible for a lower than optimal investment in energy efficiency. Policy hence leads to a situation in which capital is substituted for energy use.

To investigate macro-rebound effects, Schipper and Grubb (2000) review decomposition analysis for energy demand in seven industrialized economies. Decomposition analysis quantifies the contribution of changes in underlying variables, such as population size, economic structure, and efficiency, to changes in energy use or any other aggregate variables. The basic approach is to quantify the effect of changing one variable while holding all other variables constant. These decomposition studies

show that in the period 1973–1994, the energy intensity,[4] that is, energy use per unit of a fixed basket of goods, has decreased by between 0.6% (Norway) and 2% (Sweden) per year. Changes in the structure of the economy lead to changes in the amount of energy services consumed per GDP, ranging from reductions of 1.1% per year (Japan) to increases of 0.2% per year (the Netherlands). The consumption of energy services has increased between 1.3% (Denmark) and 2.8% (Australia) per year. As a result, the energy use per unit of GDP decreased by 1–2%. The interpretation of this evidence is that an increase in efficiency (i.e., reduction in energy intensity for specific industries and goods) translated into a corresponding reduction in energy use per GDP, and not to an increase in energy services per GDP. Hence, this analysis does not support the existence of macro-rebound effects.

Based on neoclassical growth theory, Saunders (1992) developed a stylized model of economic growth where output is dependent on the inputs of labor, capital, and energy. He showed that the effect of energy efficiency on energy use depends on the elasticity of substitution between energy and the nonenergy inputs. If this elasticity is less than 1, the aggregate energy use will be reduced; if it is greater than 1, energy use will be increased.[5] Howarth (1997) has criticized the use of energy as input and has instead proposed to distinguish between energy use and the use of energy services. Constructing a modified growth model, Howarth has shown that a backfire effect will only occur if (a) energy costs dominate the total cost of energy services[6] and (b) expenditures on energy services constitute a large share of economic activity. He argues that both are implausible. In addition, he cites reviews of the econometric literature which indicate that the elasticity of substitution between energy and nonenergy inputs is somewhere between 0 and 1. Bentzen (2004) also finds an elasticity of substitution significantly less than 1 for both labor and capital. Saunders (2000a) shows that Howarth's condition (a) depends on the assumption that, in the production of energy services, energy and nonenergy inputs cannot be substituted for each other. If such a substitution is allowed using a Cobb-Douglas production function, the backfire effect reemerges.

One important limitation of the Saunders-Howarth debate is its reliance on a highly stylized model that represents the entire economy by a single sector and hence has little empirical content. Grepperud and Rasmussen (2004) have conducted an evaluation of the effect of autonomous energy efficiency improvements in various industry sectors using the multisector growth model, a general equilibrium model of the Norwegian economy. This model includes the possibility of substitution between oil and electricity, and the analysis is based on efficiency improvements in only one of these technologies. It suggests strong rebound effects in the paper and chemical industries, weak or no rebound effects in finance, fisheries, and transportation, and a backfire effect in the metals industry.[7] How realistic this modeling experiment is remains open for debate. The model predicts an outcome 50 years in the future and far outside the range of the historical situation, based on parameters derived from an analysis of the past economy.

Saunders and Howarth disagree about the notion of an energy service. In Saunders's (1992) formulation, the energy service is simply energy use times energy productivity. Ayres and Warr (2005) argue that what actually drives growth is physical work, and that physical work can be obtained from energy resources using an efficiency factor. This is similar to Saunders's notion of energy use. It is in the nature of the model that, as energy productivity increases, the energy service is substituted for other inputs. Saunders (2000b) even argues that this substitution effect is stronger than the effect on growth, so that energy efficiency leads to increased energy use but little growth. At the same time, he dismisses the ratio of fuel use per GDP as an indicator for the backfire effect. He argues that the observed reduction in fuel use per GDP after 1973 could also be caused by increasing energy price, which counteracts the increase in fuel use due to increased efficiency. In my opinion, the energy intensity cannot be dismissed as an indicator, because otherwise there is no possibility of empirically testing the backfire theory.[8] Of course, prices change, but in the historical period reviewed by Howarth, the price of labor has increased faster than that of energy, suggesting that there should be a price-induced substitution of energy for labor and hence an increase

in fuel use per GDP. The use of a Cobb-Douglas function for the production of energy services (Saunders 2000a) is also questionable. It suggests that, as energy efficiency increases, more energy will be used to deliver an energy service. This would mean that, as the fuel economy of a car improves, more energy will be used for getting from A to B. How, in this situation, could energy be substituted for capital or labor? Howarth's (1997) technologically-based notion of energy services is more useful for empirical work, but it is not entirely clear how it can be related back to the variables in his macroeconomic model.

Based on the analysis of the input of physical work (exergy) in the U.S. economy from 1900 to 1998, Ayres and Warr (2005) suggest that most of the "Solow residual," that is, the 60% of economic growth that cannot be explained by the increased use of capital and labor included in standard growth theory, can be attributed to the increased input of physical work. The increased input of physical work is the combined result of gains in technical energy efficiency, which has increased from 3% to 22%, and increased energy consumption. If they are correct, energy efficiency can indeed substantially contribute to growth, and therefore increase the amount of goods and services consumed. This still leaves open the question of whether an accelerated rate of efficiency increase will contribute to more or less energy consumption in the aggregate. The article by Ayres and Warr apparently is controversial—perhaps because of its far-reaching implications. As far as I understand, the contribution of energy efficiency to economic growth is contested. As a consequence, the importance of macro-rebound effects is difficult to evaluate. *It is not in doubt, however, that energy efficiency leads either to substantial economic growth or to substantial reductions of energy use*. If one wants to be sure to reduce pollution, other policy measures are also needed, as Brookes (2000) points out, such as setting effective emission limits or levying pollution taxes.[9]

A review of the rebound effect in energy economics shows that there is a great deal of empirical evidence and theoretical support for a weak direct rebound effect, due both to a substitution from other products to the now cheaper energy service and to the income effect. The evidence regarding indirect rebound effects or macro effects is not conclusive. Arguments that energy efficiency results in net undesirable effects are not credible.

The Rebound Effect in Industrial Ecology

Industrial ecology differs from energy economics in two key aspects: First, it is concerned about a wide range of environmental problems, not only the consumption of energy. It is not generally true that all effects are reduced simultaneously. Instead, the general case is that a technical measure reduces some environmental pressures while increasing or keeping constant other environmental pressures. In the example of the phase-out of the chlorofluorocarbons responsible for the ozone hole, the first generation of alternative refrigerants caused higher impacts on global warming, were more toxic, or had other problems.[10] The rebound effect in economics is inherently a single-indicator concept that is not able to deal with these risk trade-off situations. Second, most environmental impacts do not generally cause internal costs, so that the reduction of environmental pressure does not necessarily imply a cost reduction and therewith an increased demand for the service. External costs are those borne by individuals who are not part of the decision-making process, which means they do not influence the consumption decisions. If I drive to work in a car that emits less air pollution, unless the pollution is taxed, the emissions reduction has no direct effect on my financial well being and thus no income or substitution effect. Although it is the claim of some industrial ecologists that increased eco-efficiency will also lead to cost reduction (Panayotou and Zinnes 1994), this is not generally the case.

The rebound debate reflects a concern about indirect effects that affect the ability of a primary policy measure to achieve its goal. In reflecting on this concern in a wider environmental context, several indirect effects come to mind.

1. The measure can lead to a cost reduction, which would then lead to a direct rebound effect in the sense used by energy economists. The primary difference is that

the ecological benefit would be described in a multi-indicator way. Changes in consumption due to the income effect could be either positive or negative. Some individuals may use their extra income to purchase more costly organic food, for example, whereas others may spend their vacations in more exotic destinations.

2. A policy measure can also lead to increased cost. In that case, the income effect is negative, that is, reduces available income and thereby potentially (but not necessarily) reduces the magnitude of environmental effects caused by other purchases.

3. Policy measures primarily addressing a single issue, such as phasing out ozone-depleting substances, can increase other types of impact, such as global warming or human health. Such negative side effects certainly do reduce the overall benefit of the policy measure, and this could be made visible in a single-indicator system such as the Eco-indicator 99 (Goedkoop and Spriensma 1999) or the Environmental Priority Strategies (EPS) in product design (Steen 1999). The side effect, however, does not limit the efficacy of the ozone-protection measure in achieving its primary goal. Of course there are often positive side effects, or co-benefits, such as the reduction of conventional air pollution through climate policy (Aunan et al. 1998; Wang and Smith 1999).

4. Behavioral changes can have indirect effects that are not mediated through the price mechanism. Thøgersen and Ölander (2003) have demonstrated a slight spillover effect from one area of environmentally friendly behavior to others, that is, a positive, indirect behavioral effect.

5. Technical changes can enable other emissions-reducing technology. In an analysis of hydrogen fuel-cell vehicles, my research group has found such vehicles to be environmentally preferable to hybrid combustion engine-electric cars in Europe, but not the United States, because electricity is cleaner in Europe (Hertwich and Strømman 2004). A hydrogen distribution system would use more electricity than fossil fuel distribution systems do. This is a technical spillover: as a result of cleaner electricity, cleaner transportation technology becomes feasible.

The identification of co-benefits and negative side effects of technical or policy measures is a bread-and-butter issue for life-cycle assessment (LCA). Behavioral rebound or spillover effects have not been analyzed as part of IE, but they are a key issue in sustainable consumption. To our knowledge, technological spillover effects have not been addressed systematically, except perhaps in energy scenario modeling with technological learning, where it was recognized that the relative merit of different technologies is path-dependent. Approaches to modeling or empirically analyzing the other indirect effects are only now being developed or adopted from other disciplines.

Hofstetter and colleagues (2002) review the assessment of direct and indirect effects of environmental policy measures. They identify ten different "ripple" effects and review how different assessment methods take these effects into account.[11] Focusing on human health effects, they point out that costly environmental protection measures can have negative health effects because they reduce the purchase of healthy food and health care (see also Hammitt and colleagues 1999). Their review reveals that a concern for multiple indicators leads to a more intelligent analysis. Whereas the rebound perspective sees additional income as undesirable, because it may be spent on energy services, a broader perspective also includes the benefits of additional income. Takahashi and colleagues (2004, p. 1968) use the term "ripple effect" to address changes that come about due to the interaction of technical progress and behavioral changes. The term "ripple effect" may therefore be well suited to encompass all these indirect effects.

Direct rebound effects have been quantified in environmental input-output analysis since 1974 (Bezdek and Hannon 1974, Hertwick 2005). In this approach, household environmental impacts (HEI) are calculated by combining household expenditures with energy and/or emissions intensities of different expenditure items. These intensities have been calculated using input-output

analysis. When a change reduces for example the expenditure of energy, the remaining expenditures are increased so that the total expenditure level remains constant. In this issue of the *Journal of Industrial Ecology*, Takase and colleagues present such an analysis (Takase et al. 2005). Many studies of the rebound effect often limit themselves to a single impact category, such as greenhouse gas emissions (Noorman and Uiterkamp 1997; NOVEM 2000; Chalkley et al. 2001). Goedkoop and colleagues (Goedkoop et al. 1999) introduced the eco-efficiency vector (E2 vector), which goes back to Bezdek and Hannon's graphical presentation of energy, value added, and employment (Bezdek and Hannon 1974). The E2 vector graphs the environmental impact of a process per unit value added. Goedkoop and colleagues use the Eco-indicator 99, a life-cycle impact assessment method that aggregates impacts into a single indicator, to represent environmental impacts. Individual impact categories or inventory items can be graphed as well. This approach has been used to illustrate a number of studies, including the assessment of product-service systems and car sharing.

The vectors in figure 1 present the value creation in different industries in Norway and their environmental load measured in CO_2 equivalents. The slope of the vector is a representation of the pollution intensity, whereas the length on the x-axis represents the economic value added. The life cycle of a product or service can be represented by a series of vectors in sequence (figure 2a). The trade-off between different environmental impacts is a core concern of life-cycle assessment. It is included in this representation if Eco-indicator 99 is used, but it does not become visible.

Figure 2 illustrates how the E2 presentation can be applied to the rebound effect. Graph a presents how a product life cycle can be assembled from individual process or industry eco-efficiencies. Each individual arrow presents a process, with the value added in the process on the x-axis and the environmental load on the y-axis. Consumption, in this case driving a car, now has value added, but it has direct emissions associated with it. Graphs b–d display the rebound effect for different types of goods.[12] Each vector now represents a specific product or
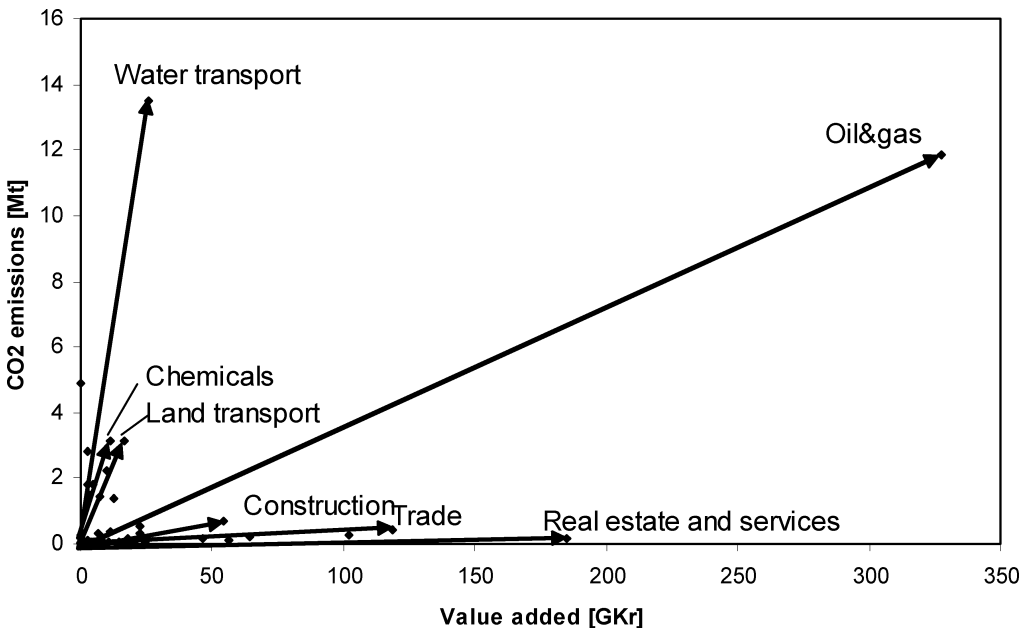

Figure 1 The E2 vector: Environmental load and value creation of different sectors in the Norwegian economy (author's calculations). Mt = million metric tonnes; Gkr = billion Norwegian Kroners.
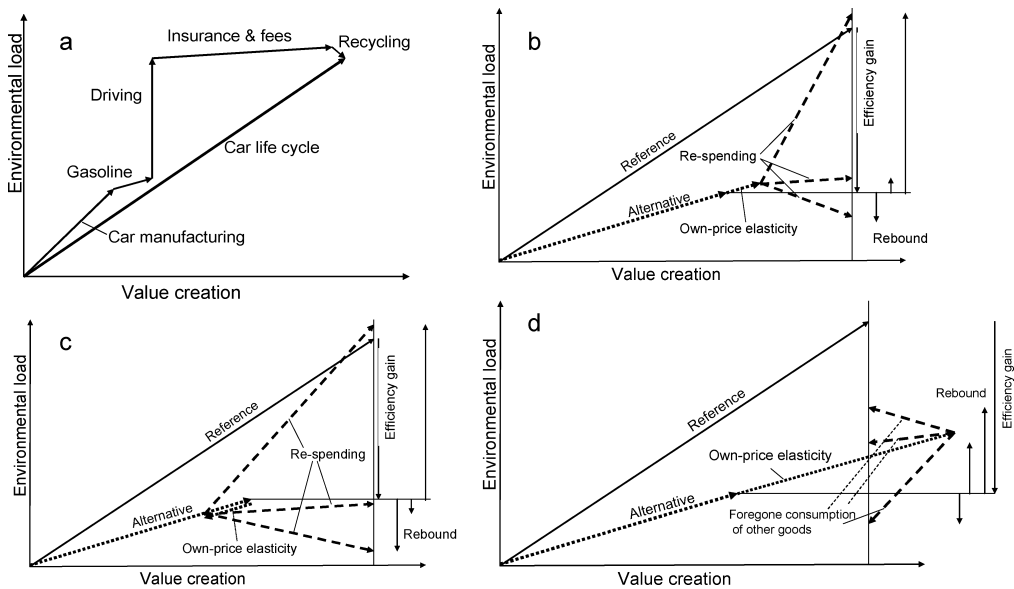
Figure 2 (a) E2 vector of the life cycle of a product, using a car as an example. Direct rebound effects for (b) normal goods, (c) inferior goods, and (d) luxury goods. The three vectors for re-spending indicate the possibilities of purchasing items with higher impact than the alternative, lower impacts, and negative impact, respectively.

service or a whole basket of goods. In each case, we assume that a reference good is replaced by an alternative good that has a lower price and a lower impact per unit of service. Assuming a constant spending level, consumers will spend the money saved either on the same or on other goods. The magnitude of the rebound effect now depends both on the change in consumption of the alternative and on the emissions intensity of the other goods purchased with the saved money.

Graph b shows what economists call a "normal" good. As the product gets cheaper, more of it will be consumed, but some money will also be spent on other goods. This depends on the own-price elasticity of the good. The saved money can be spent on goods that have a larger or a smaller emissions intensity than the alternative good. It is also possible that the alternative expenditure has a negative emissions intensity if it is used for reducing emissions, for example, for insulating a home.[13]

Graph c shows the case for an inferior good. As the product becomes cheaper, less of it will be consumed because the consumer uses the saved money to purchase a more attractive alternative. A negative (i.e., desirable) rebound effect can result even with a positive slope of the respending vector, because of the reduction in the consumption of the product, if the original product was more impacting than the competing superior good. Binswanger (2001) has shown how this negative rebound effect comes about, using indifference curves. He suggested that different leisure activities could provide an example for this case.

Graph d shows the case of a luxury good, where disproportionately more money will be spent on purchasing additional units of this good. Consumption in other areas will be forgone. Also, in this case, there can be a negative rebound effect if the consumption that is forgone in favor of purchasing the luxury good has a larger environmental load than the additional purchases of this good. How important this potential negative rebound effect is is uncertain. A number of luxury goods have a high impact, such as gold or airplane trips, but it is unlikely that they would replace an even more damaging activity. Other luxury goods have lower impacts, but their price is probably not strongly dependent on the environmental impact, so that the price reduction will be smaller.

Although there has been much less attention to the rebound effect in IE, the direct rebound effect is routinely included in the assessment of both consumption and product service systems. Several other indirect effects are as significant as the rebound effect. Of these effects, only the side effects on other types of environmental impact are routinely included. Technological and behavioral spillover effects are not included.

Rebound Phenomena Related to Sustainable Consumption and Production

What does this all mean for sustainable consumption and production? This is an interesting question, especially because policy makers and research funders draw a connection between the rebound effect and sustainable consumption. Sustainable consumption does not primarily focus on technical measures to increase efficiency, but on behavioral measures. These include, but are in no way limited to, the purchase of "greener" products. I see several connections.

Cleaner or sustainable production, including the development of greener products, product-service systems, and services in place of products, has been a significant focus. Some efforts are also directed at inventing new products or distribution channels. It makes sense to take environmental issues into account in the innovation process. All these efforts have a behavioral component, because cleaner product solutions need to be accepted by the market. Some policy makers see the role of sustainable consumption primarily as promoting these new products. Although I do think that sustainable consumption needs to go much further, it can gain a lot of insight into consumer behavior by accepting this task. For cleaner product solutions, secondary effects can have a substantial impact. Behavioral spillover effects, as identified by Thøgersen and Ölander (2003), are obviously of interest. Both direct rebound effects and shifts in environmental impacts can be included in an assessment. What is more important, in my opinion, is the question of the impact of new solutions on how individuals organize their lives, the domestication of technology. New product solutions can have enabling effects, and what they enable consumers to do can be

critical for the environmental impact. This has been indicated by the research on the time-rebound effect, both in transportation research and by Jalas (2002, 2005) and Perrels (2002). In this area, there is room for fruitful collaboration among those who work on sustainable production and those who work on sustainable consumption.

In studies of sustainable consumption, the rebound effect is already taken into account in the analysis of household environmental impact (HEI), which often starts from consumer expenditure surveys (Hertwich and Katzmayr 2003). When the analysis focuses only on selected functions, such as nutrition or transport, special attention needs to be paid to the rebound effect, but the sustainable consumption research community has taken this into account since the 1970s (Bezdeck and Hannon 1974). The example of car sharing by Goedkoop and colleagues (1999) illustrates such assessments. Car sharing reduces the frequency of car use and it reduces expenditure on car use. The question is then how the consumers will use the money saved. For a modeling exercise, it can be assumed that the saved money is spent on different goods in the same proportion as the average expenditure. Better, the modeling can be based on an assessment of the marginal expenditures of households in different income categories. Alternatively, a case-control study can be used to evaluate the different expenditure patterns of people who own cars and those who engage in car sharing, controlling for income. It is a strength of HEI analysis that it includes the direct rebound effect.

Research on sustainable consumption has also focused on growth. The perspectives are not so dissimilar, because SC researchers have been occupied with finding out why consumers want to consume ever more and whether this is good for them (Jackson 2005). Philosophers have developed ethical arguments for why we should grow less and distribute wealth across different parts of the world. Energy economics is interested in the effect of growth on energy use. I doubt, however, that the neoclassical growth or general equilibrium models used by energy economists have much to contribute to sustainable consumption research. I think, rather, that sustainable consumption research needs to gain a better understanding of the social changes and of the

interaction between the social and material dimensions. It is questions of what consumers want more of, what they need less of, how this affects their ability to navigate the challenges of modern life, and how it affects environmental impact.

Conclusions

The concept of the rebound effect, as defined in energy economics, is insufficient to describe the different secondary effects that are of interest in industrial ecology or sustainable consumption. Additional mechanisms and multiple environmental endpoints need to be considered. One can talk about "rebound phenomena," but even this distracts attention from the fact that a substantial part of these unintended or secondary effects are in fact positive, that is, lead to a reduction of impacts. A more neutral term, such as "ripple effects," is therefore preferable.

What emerges from this review of the rebound effect is that these other secondary effects that are less well defined, let alone investigated, are both important and interesting. They include behavioral and technological spill-over effects, transformational effects, and positive and negative side effects, that is, environmental or other repercussions not directly addressed by the primary policy measure. These effects fall outside economic equilibrium modeling: the spillover effects and transformational effects point to path-dependent development. LCA and HEI analysis can address direct rebound effects as well as positive and negative side effects. Consumer psychology has developed ways to detect behavioral spillover. Energy scenario modeling has developed approaches to exploring the path dependence and transformation that comes with technological learning. It is not clear that these approaches are sufficient. In any case, ways to explore these effects from a common perspective are lacking. This investigation of the rebound effect has hence identified the need for new research that is outside the established notion of the rebound effect.

Notes

1. The "double dividend" refers to gains in both economic terms and environmental terms, that is, to actions that reduce both costs and emissions of resources use.

2. The idea of an energy service is similar to that of a functional unit in LCA. Consumers, presumably, want light, a pleasant indoor climate, a warm meal, etc., not kilowatt hours or tons of oil equivalent. The energy service hence serves as a basis for comparison of different technologies which fulfill the same function, such as providing illumination or thermal comfort. In decomposition analyses discussed later in the article, all energy use is for the production of energy services. This could be interpreted as all consumption consisting of energy services, but this is not the case. Instead, industry and commerce consume energy services and produce non-energy goods. In industry, energy services can be defined as the production of basic materials from their ores or as the delivery of power and steam.

3. *Editor's Note:* For a discussion of a book length contribution to this debate, see the review by Strauss (1998) of *Why Energy Conservation Fails* in this journal.

4. The term "energy intensity" is somewhat ambiguous, because it can refer both to the energy/GDP ratio and to the energy use per value added in a specific industry or for a specific product. Since the composition of the GDP changes with time, and the relative prices change, it is sensible to measure technical efficiency by looking at energy per unit of a specific product (e.g., ton of steel) or energy service (e.g., house of a certain size warmed to 21°C in a specific climate). In this case, energy intensity refers to the changes in energy use per fixed unit of output, not the entire GDP.

5. Bentzen (2004) finds an elasticity of substitution significantly less than 1 for both labor and capital.

6. The costs of energy services also include capital costs (e.g., costs of washing machines, cars, heating equipment) and labor costs.

7. I suspect that the backfire in the metals industry is a model artifact. In this sector, which is dominated by the aluminum industry, oil consumption rises more than output because electricity becomes cheaper. The problem is that the model first combines oil and electricity and then trades off this combined energy with other inputs. In this case, there is no substitution between oil and electricity, but energy is substituted for other inputs.

8. The aggregate use of energy per GDP is flawed for another reason: it does not reflect changes in the composition of economic activity or consumption, which may result in the relocation of pollution-intensive activities to or from the country to

other countries. This can have an influence that is as large as the expected changes in efficiency (Hertwich et al. 2002; Murtishaw and Schipper 2001). Therefore, decomposition analysis is better suited as a test for rebound and backfire effects.

9. If indeed the distinction between energy and useful work is important (Ayres et al. 2003), we need to distinguish between the efficiency with which energy is converted to useful work and the efficiency with which useful work is converted to services. Some energy efficiency measures address the former (for example, information campaigns about energy use in white goods), others address the latter (for example, standards for building insulation), and some address both (for example, standards for automotive fuel consumption). This distinction would be important first for analytical purposes. Please note that all products and services consumed require energy in their production. The energy intensities (energy per unit value) of energy services are not as high as one would expect.

10. *Editor's note:* For an analysis of the global warming impacts of alternative refrigerants, see the work of Papasavva and Moomaw (1997).

11. The effects are classified in a very different manner than here and include upstream risks, downstream risks, and occupational effects. But they also include technological innovations and structural changes, as well as risk-offsetting behavior.

12. I am using the term "good" to refer to both products and services.

13. In this graph, I use the term own-price elasticity to indicate the change in the quantity of the good consumed. This changes comes about both because of a substitution to the good when it becomes cheaper and a shift to or away from the good as the effective income increases, because of the cost reduction.

14. Peer review of this article was managed by the editor-in-chief of the *Journal of Industrial Ecology* according to the journal's standard procedures.

References

Aunan, K., G. Patzay, H. A. Aaheim, and H. M. Seip. 1998. Health and environmental benefits from air pollution reductions in Hungary. *Science of the Total Environment* 212(2–3): 245–268.

Ayres, R. U., L. W. Ayres. and B. Warr. 2003. Exergy, power and work in the US economy, 1900–1998. *Energy* 28(3): 219–273.

Ayres, R. U. and B. Warr. 2005. Accounting for growth: The role of physical work. *Structural Change and Economic Dynamics* 16(2): 181–209.

Bentzen, J. 2004. Estimating the rebound effect in US manufacturing energy consumption. *Energy Economics* 26(1): 123–134.

Bezdek, R. and B. Hannon. 1974. Energy, manpower, and highway trust fund. *Science* 185(4152): 669–675.

Binswanger, M. 2001. Technological progress and sustainable development: What about the rebound effect? *Ecological Economics* 36(1): 119–132.

Brookes, L. G. 1978. Energy policy, the energy price fallacy and the role of nuclear energy in the UK. *Energy Policy* 6(2): 94–106.

Brookes, L. G. 1990. The greenhouse effect: The fallacies in the energy efficiency solution. *Energy Policy* 18(2): 199–201.

Brookes, L. G. 2000. Energy efficiency fallacies revisited. *Energy Policy* 28(6–7): 355–366.

Chalkley, A. M., E. Billett, and D. Harrison. 2001. An investigation of the possible extent of the respending rebound effect in the sphere of consumer products. *Journal of Sustainable Product Design* 1: 163–170.

Goedkoop, M. J., C. J. G. van Halen, H. R. M. te Riele, and P. J. M. Rommens. 1999. *Product service systems: Ecological and economic basics.* Amersfoort, The Netherlands: PRé Consultants.

Goedkoop, M. and R. Spriensma. 1999. *The EcoIndicator 99.* Amersfoot, The Netherlands: PRe Consultants.

Goodwin, P. B. 1978. Travel choice and time budgets. In *Determinants of travel choice* edited by D. Henscher and Q. Davli. Farnborough, UK: Saxon House.

Greening, L., D. Green, and C. Difiglio. 2000. Energy efficiency and consumption—The rebound effect—A survey. *Energy Policy* 28: 389–401.

Grepperud, S. and I. Rasmussen. 2004. A general equilibrium assessment of rebound effects. *Energy Economics* 26(2): 261–282.

Grubb, M. J. 1990. Energy efficiency and economic fallacies. *Energy Policy* 18(8): 783–785.

Haas, R. and P. Biermayr. 2000. The rebound effect for space heating—Empirical evidence from Austria. *Energy Policy* 28(6–7): 403–410.

Haas, R. and L. Schipper. 1998. Residential energy demand in OECD-countries and the role of irreversible efficiency improvements. *Energy Economics* 20(4): 421–442.

Hammitt, J. K., E. S. Belsky, J. I. Levy, and J. D. Graham. 1999. Residential building codes,

affordability, and health protection: A risk-tradeoff approach. *Risk Analysis* 19(6): 1037–1058.

Henly, J., H. Ruderman, and M. D. Levine. 1988. Energy savings resulting from the adoption of more efficient appliances: A follow-up. *The Energy Journal* 2: 163–170.

Hertwich, E. 2005. Lifecycle approaches to sustainable consumption: A critical review. *Environmental Science & Technology*. Accepted for publication.

Hertwich, E. G. and M. Katzmayr. 2003. *Examples of sustainable consumption*. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Hertwich, E., and A. Strømman. 2004. *The environmental benefit of direct hydrogen fuel cell vehicles—An analysis of the assessment literature*. Trondheim, Norway: Norwegian University of Science and Technology, Industrial Ecology Programme.

Hofstetter, P., J. C. Bare, J. K. Hammitt, P. A. Murphy, and G. E. Rice. 2002. Tools for comparative analysis of alternatives: Competing or complementary perspectives? *Risk Analysis* 22(5): 833–851.

Hofstetter, P. and M. Madjar. 2003. *Linking change in happiness, time-use, sustainable consumption, and environmental impacts: An attempt to understand time-rebound effects*. Zurich: Consultrix.

Howarth, R. B. 1997. Energy efficiency and economic growth. *Contemporary Economic Policy* 15(4): 1–9.

Jackson, T. 2005. Live better by consuming less? Is there a "double dividend" in sustainable consumption? *Journal of Industrial Ecology* 9(1–2): 19–36.

Jalas, M. 2002. A time use perspective on the materials intensity of consumption. *Ecological Economics* 41: 109–123.

Jalas, M. 2005. The everyday life-context of increasing energy demands: Time use survey data in a decomposition analysis. *Journal of Industrial Ecology*. 9(1–2): 129–146.

Khazzoom, J. D. 1986. *An econometric model integrating conservation in the estimation of the residential demand for electricity*. Greenwich, CT: JAI Press.

Khazzoom, J. D. 1980. Economic implications of mandated efficiency in standards for household appliances. *Energy Journal* 1(4): 21–40.

Lovins, A. B. 1988. Energy savings from more efficient appliances: Another view. *Energy Journal* 9: 155–162.

Noorman, K. J. and T. S. Uiterkamp, eds. 1997. *Green households?* London: Earthscan.

NOVEM (Netherlands Agency for Energy and the Environment). 2000. The Perspective Project: Towards an energy aware lifestyle. Sittard, The Netherlands: NOVEM.

Panayotou, T. and C. Zinnes. 1994. Free-lunch economics for industrial ecologists. In *Industrial ecology and global change*, edited by R. Socolow, C. Andrews, F. Berkhout, and V. Thomas. Cambridge: Press Syndicate of the University of Cambridge.

Papasavva, S. and W. R. Moomaw. 1997. Life-cycle global warming impact of CFCs and CFC-substitutes for refrigeration. *Journal of Industrial Ecology* 1(4): 71–92.

Perrels, A. 2002. Understanding consumption patterns—Including time use, skills, and market failures. In *Life-cycle approaches to sustainable consumption—Workshop proceedings*. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Roy, J. 2000. The rebound effect: Some empirical evidence from India. *Energy Policy* 28(6–7): 433–438.

Saunders, H. D. 1992. The Khazzoom-Brookes postulate and neoclassical growth. *Energy Journal* 13(4): 131.

Saunders, H. D. 2000a. Does predicted rebound depend on distinguishing between energy and energy services? *Energy Policy* 28(6–7): 497–500.

Saunders, H. D. 2000b. A view from the macro side: Rebound, backfire, and Khazzoom-Brookes. *Energy Policy* 28(6–7): 439–449.

Schipper, L. and M. Grubb. 2000. On the rebound? Feedback between energy intensities and energy uses in IEA countries. *Energy Policy* 28(6–7): 367–388.

Steen, B. 1999. A systematic approach to environmental priorities in product development (EPS). Version 2000—general system characteristics. CPM 1999:4. Gothenburg, Sweden: Chalmers University.

Strauss, T. 1998. Review of *Why Energy Conservation Fails* by Herbert Inhaber. *Journal of Industrial Ecology* 2(1): 147.

Takahaski, K. I., T. Kunioka, H. Tatemichi, T. Tanaka, and S. Nishi. 2004. Environmental assessment of ICT Services: New Methodology considering ripple effects. Paper read at the Sixth International Conference on EcoBalance, Tsukuba, Japan.

Takase, K., Y. Kondo, and A. Washizu. 2005. An analysis of sustainable consumption by the waste input-output model. *Journal of Industrial Ecology* 9(1–2), pp. 201–219.

Thøgersen, J. and F. Olander. 2003. Spillover of environment-friendly consumer behaviour. *Journal of Environmental Psychology* 23(3): 225–236.

Walker, I. O. and F. Wirl. 1993. Irreversible price-induced efficiency improvements: Theory and empirical application to road transportation. *The Energy Journal* 14(4): 183–205.

Wang, X. D. and K. R. Smith. 1999. Secondary benefits of greenhouse gas control: Health impacts in China. *Environmental Science & Technology* 33(18): 3056–3061.

About the Author

Edgar G. Hertwich is leader of the Industrial Ecology Program and a professor in the Department of Energy and Process Engineering at the Norwegian University of Science and Technology in Trondheim, Norway. He is the editor of this special issue of the *Journal of Industrial Ecology* on sustainable consumption.[14]