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Energy Conservation More Effective With Rebound Policy

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Abstract This article sketches the problem of indirect energy use effects, also known as rebound, of energy conservation. There is widespread support for energy conservation, especially when it is voluntary, as this seems a cheap way to realize environmental and energy-climate goals. However, this overlooks the phenomenon of rebound. The topic of energy rebound has mainly attracted attention from energy analysts, but has been surprisingly neglected in environmental economics, even though economists generally are concerned with indirect or economy-wide impacts of technical change and policies. This paper presents definitions and interpretations of energy and environmental rebound, as well as four fundamental reasons for the existence of the rebound phenomenon. It further offers the most complete list of rebound pathways or mechanisms available in the literature. In addition, it discusses empirical estimates of rebound and addresses the implications of uncertainties and difficulties in assessing rebound. Suggestions are offered for strategies and public policies to contain rebound. It is advised that rebound evaluation is an essential part of environmental policy and project assessments. As opposed to earlier studies, this paper stresses the relevance of the distinction between energy conservation resulting from autonomous demand

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changes and from efficiency improvements in technology/equipment. In addition, it argues that rebound is especially relevant for developing countries.

Keywords Backfire · Developing countries · Jevons' paradox · Rebound mechanisms · Relieving limits · Tradable permits

JEL Classifications Q43 · Q48 · Q54 · Q55 · Q58

1 Motivation

Once again, energy conservation is high on the political agenda, due to the need to curb CO_2 emissions. This article will sketch the problem of rebound effects of energy saving strategies and discuss its implications for the design of public, governmental policies aimed at stimulating energy conservation and improvements in energy efficiency. Virtually everyone seems to be in favor of energy conservation, especially when it is voluntary as this is generally seen as virtually costless, or as economists like to say: a free lunch. Most concrete proposals for reducing energy use are nevertheless very local and partial in nature and do not account for indirect, unintended effects. The latter is sometimes referred to as "rebound". Its occurrence suggests that one has to be skeptical or even pessimistic about cheap solutions to pressing environmental problems like climate change through energy conservation. Evaluation of rebound should be an essential part of sustainability thinking in the sense that always system-wide effects have to be considered before judging any strategy or policy. Rather than just offering a pessimistic message about rebound, however, this article aims to provide an understanding of the rebound problem and offer suggestions for strategies and public policies to contain or reduce the rebound effect so as to make energy conservation maximally effective.

The idea of energy rebound goes back to Jevons (1865) suggestion that improved efficiency of coal-fired steam engines would not result in less but more use of coal and therefore contribute to a more rapid depletion of England's coal reserves. The reason is that a higher efficiency means a lower effective cost of coal, which stimulates diffusion of the coal using technology throughout the economy. Brookes (1979) and Khazzoom (1980) proposed that a similar feedback mechanism might be relevant to the context of energy conservation, in particular improvements in the energy efficiency of all kinds of machinery and equipment. Subsequent papers on the topic have mainly appeared in energy journals, mostly in *Energy Policy* and *The Energy Journal* Khazzoom 1980, 1987, 1989; Lovins 1988; Brookes 1990, 2000; Saunders 1992, 2000; Herring 1999, 2006; Berkhout et al. 2000; Birol and Keppler 2000; Jaccard and Bataille 2000; Sanne 2000; Grepperud and Rasmussen 2004; Dimitropoulos 2007; Sorrell 2009. Different views on energy rebound have been expressed—see, for example, the debate in a special issue of *Energy Policy* (Schipper 2000). Nevertheless, many environmental economists are still unaware of the notion of rebound and its potential relevance to the design of environmental and climate strategies and policies. This is the more surprising given that economists generally are interested in indirect or economy-wide impacts of technical change and policies. Moreover, in the context of climate policy they have given attention to leakage effects, which are similar to rebound effects (see Sect. 2).

Rebound may be particularly relevant to energy conservation in developing countries, for a number of reasons. First, some of these countries show a high rate of growth, which means that they offer much potential for rapid accumulation of energy-using technologies and more energy-intensive consumption. The direction of development could in fact widely range from very energy-efficient to very inefficient—as opposed to industrialized countries where this margin is likely to be narrower. Second, the cost of energy is relatively high for poor countries, due to low wage labor, which may cause a relatively large financial gain to be associated with energy conservation and in turn, among others, a considerable re-spending effect, by both firms and consumers. Third, developing countries are far from saturation in their consumption of key energy services such as lighting. Many households do not have access to these services at all, but could potentially gain access if their price was lowered through energy efficient technologies. Fourth, developing countries may "technologically leap-frog", in terms of energy-efficient technologies as well as new energy using devices. Fifth, lower education and less availability of information in developing countries possibly contribute to decision-making by firms, households and governments that does not take all relevant economic and associated energy use effects into account. It should be noted, however, that also in industrialized countries private and public decision-makers are largely unaware of rebound effects of their decisions. One is even tempted to say that energy conservation is more driven by good intention than by good oversight of all its consequences.

The reminder of this paper is organized as follows. Section 2 offers definitions and interpretations of energy and environmental rebound. Section 3 offers the most complete list of rebound pathways or mechanisms available in the literature. Section 4 presents four fundamental reasons for the existence of the rebound phenomenon. Section 5 discusses empirical estimates of rebound and Sect. 6 addresses implications of uncertainties and difficulties in assessing rebound. Section 7 examines which types of policies can reduce or optimize rebound effects of energy conservation. Section 8 concludes.

2 Definitions and Interpretations of Energy and Environmental Rebound

"Energy rebound" denotes the phenomenon that greater energy efficiency, or plain energy conservation through changes in behavior or choices (by firms or consumers), triggers additional energy use so that the net effect on total energy use over time becomes uncertain. Since we are concerned with definite solutions to serious environmental problems like human induced climate change, we need to assess the long-term and system-wide effects of any energy strategy to assess whether it makes sense from an energy conservation or environmental perspective. Improvements in energy efficiency may cause additional negative environmental effects when less energy use goes along with more material use, more use of space/land, dangerous pollution (e.g., toxic materials), more transport and associated risks and noise, etc. This is sometimes referred to as shifting problems from one area to another, or "environmental rebound". A basic example is reducing air or water pollution but thus creating more solid waste, in line with the mass balance principle.

Rebound due to energy efficiency improvements (but not other types of energy conservation) may be understood in terms of technical-engineering versus behavioral-economic phenomena. Here the initial energy saving is due to technical or engineering improvements in energy using equipment. This saving then initiates or causes behavioral and economic responses—such as more intense use of more efficient equipment, re-spending saved money or diffusion of more efficient and therefore attractive technologies— which all together affects energy use.

Technical-engineering improvements in energy efficiency are not the only possible starting point. Energy conservation can also result from changes in behavior (less driving, lowering the heating), which then can stimulate subsequent behavioral-economic changes that may partly or wholly undo the initial gains. The difference is that whereas with energy efficiency improvements the same functions or services can be fulfilled with less energy (exergy) inputs, in the case of energy conservation without efficiency improvements the cost per unit of energy is not reduced and typically functions or services alter (are reduced in size or number). Examples are fewer kilometers driven and a lower space temperature in the house. Energy efficiency improvements are therefore likely to generate rebound to a larger degree than other types of energy conservation.

Even though our concern should ultimately be with rebound at the global scale, it is clear that rebound is a phenomenon which occurs at multiple scales. When households or firms undertake energy conservation activities these may cause additional energy use within their own sub-system, even without them being aware of it. One policy response could therefore be to make agents conscious or aware of rebound effects occurring within their own realm. In addition, rebound occurs at industrial park, urban, regional, national and international or global levels. Assessment of the rebound channels at each higher level becomes increasingly more difficult—both theoretically and empirically—because of more complex interactions and feedback mechanisms, and ever larger numbers of economic agents and activities. This motivates the uncertainty of rebound estimates as will be discussed in more detail in Section 6. It also suggests that a system-level solution is needed to counter rebound.

Different terms next to rebound (effect) have been employed to denote identical or similar notions, or subsets of rebound effects: indirect or second-order effect, Khazzoom–Brookes effect (Khazzoom 1980; Brookes 1979, 1990), backfire and Jevons' paradox.[1] The latter two terms specifically denote 100% or more rebound, meaning that energy conservation ultimately gives rise to more energy use. Nevertheless, some authors use "Jevon's paradox" more generally, i.e. synonymously with "rebound". Other areas of research address similar issues referred to sometimes as "(carbon) leakage", notably in the context of climate mitigation policy where relocation of "dirty industries" (often to developing countries with less stringent environmental regulation) and associated changes in foreign trade flows cause initial, direct reductions in GHG emissions to be compensated by increases in GHG emissions elsewhere (Felder and Rutherford 1993; Babiker 2001; Paltsev 2001; Kuik and Gerlagh 2003). Eichner and Pethig (2009) refer to the "green paradox", meaning that policies aimed at curbing GHG emissions may aggravate rather than alleviate global warming.

The term rebound effect, although now quite widely accepted and precisely defined, is less popular among economists, who seem to prefer the more traditional notions of general equilibrium, economy-wide and macroeconomic effects. However, rebound really denotes a broader set of effects, including, for example, dynamic effects caused by technological diffusion. This will become clear in the next section.

3 Types of Rebound Pathways

As was already hinted at, rebound effects come in many different forms and therefore are not always easily recognized. The growing literature on rebound effects offers a range of classifications with different terminologies. An effort to provide a complete list of rebound mechanisms, together forming a sort of complete systems perspective on the possible indirect energy use effects of energy conservation, is as follows:

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[1] Other, less common terms are take-back and snapback effects (Nadel 1994).

1. More intensive use of energy-consuming equipment by current users because of a higher energy efficiency and thus a lower effective energy cost; Sorrell (2007) calls this a direct rebound effect.
2. Purchase of larger units or units with more functions/services and consequently using more energy (e.g., cars with air-conditioning).
3. Re-spending of financial savings due to energy conservation on other energy-intensive goods and services (income effects).
4. Creation of extra demand for relatively energy-intensive goods—both from existing and new users—if initial energy savings are so large that the energy price and in turn the prices of energy-intensive goods drop. Note that energy efficiency improvements of equipment may go along with quality improvements which may also affect purchase decisions of consumers (or producers). This all results in composition effects, namely a shift from energy-extensive to -intensive goods.
5. Changes in the processes of one phase of the product chain or life-cycle (virgin resource extraction, production/manufacturing, product use, waste treatment and reuse/recycling) may affect energy use in a later phase and thus over the entire chain. For example, durability and recyclability may conflict. Such effects are generally not recognized because of split incentives between various decision-makers (firms, firm departments or consumers) in different stages of chain.
6. A higher energy efficiency may lead to a change in the factor input mix (energy, capital, labor, materials) in production, due to substitution or complementary relationships. This causes indirect energy use effects as each factor is being produced and transported, which involves energy use.
7. An increase in total productivity and production output due to increased energy efficiency. This in turn will create more demand, investment and transport, leading to more (indirect) energy use. Schurr (1985) emphasizes that productivity-increasing effects sometimes are due to improved energy efficiency going along with a shift to higher quality fuels (notably electricity and fluid fuels like oil and gas).
8. Interactions between product, factor and financial markets due to the changing efficiency and thus effective price of energy. As a result, the composition of production and consumption, freight and passenger transport, and investments will be affected, all with consequences for energy use. This can be seen as a typical general equilibrium or macroeconomic effect.
9. International trade and re-location effects of changing efficiency and effective prices of energy as these change relative prices of traded commodities which in turn affect comparative advantages. Re-location changes transport flows and causes demolition of old and construction of new plants and infrastructure. This all has implications for energy use.
10. Capital investment and accumulation effects of changes in energy costs mean long term effects on production output and productivity, which will affect energy use.
11. Technological innovation and diffusion effects will occur through learning and investments in R&D responding to changing energy costs. This will change the spectrum of available processes and products with different energy use characteristics, which has long term implications for energy use.
12. Changes in the cost of energy and subsequent changes in technologies, products and services (mechanisms 4 and 8-11) may stimulate changes in preferences. This in turn will affect demand and thus energy use.
13. Any energy conservation strategy that involves the purchase and use of a more energy-efficient device, whether by a consumer or producer, will generate indirect energy use

effects through energy embodied in this device (i.e. all energy needed directly and indirectly to produce it).

14. Time savings going along energy efficiency improvements of technical equipment may mean that individuals will have more time available which they then can spend on activities that use energy.

Note that economic growth and an associated increase in energy use are sometimes mentioned as well as mechanisms of rebound. However, it seems more correct to say that many of the above mechanisms contribute to economic growth, which is then not a separate, additional effect but an aggregation of various effects. Greening et al. (2000) make a distinction between four categories of market responses to changes in fuel efficiency, namely direct rebound effects (cost or price fall effect on demand), secondary fuel use effects (on other markets, mainly through re-spending), economy-wide effects (defined by them as market-clearing price and quantity adjustments, especially in fuel markets), and transformational effects (preference change, partly induced by technological change). However, this distinction is not entirely satisfactory. For example, economy-wide effects really cover all possible effects, on inputs, productivity, incomes, expenditures, prices and quantities. Sorrell (2007) distinguishes between two types of effects of improved energy efficiency: direct effects, namely more intensive use of equipment, and indirect effects, basically all others. The sum of direct and indirect effects he then calls economy-wide effects.

The energy embodied in products and services, i.e. all the direct and indirect energy needed to produce them, seems to be often forgotten, even though it may be relevant for technologies that diffuse widely. For instance, ICT (information & communication technologies), notably computers and internet, have often been suggested to reduce environmental pressure (the paperless office). However, their rebound effect may be significant, among others, because of considerable embodied energy effects (production of computer chips being very energy-intensive) and energy use involved in operating computers (van den Bergh et al. 2009). In addition, technological diffusion combined with preference changes are important, notably in relation to the diffusion of general purpose technologies (which affect or permeate the entire economy, like electric and combustion engines, the automobile, energy storage/batteries, ICT and the Internet). Last but not least, from the angle of industry relations complex webs of firm interactions, long production chains and international logistics/transport may be very relevant to obtain a full understanding of the rebound effect of industrial energy conservation. All in all, a complex picture of rebound pathways emerges.

The time effect of more energy efficient technology will influence rebound as well. If energy efficiency improvements go along with (or cause) less time-efficiency or more time needed in operating the technology (or travelling a certain distance, in the case of transport technology), generally a smaller rebound effect results. An increase in time-efficiency, on the other hand, can generate a higher rebound effect (Binswanger 2001; Sorrell and Dimitropoulos 2007). The latter seems to be the more general case.

Note that the above list contains 14 mechanisms. If 10 are operative and contribute only 2% rebound on average one arrives already at a 20% rebound.

One might argue that possibly certain mechanisms are too easily interpreted as rebound of energy conservation, namely because multiple factors are at stake. However, if energy conservation is an essential or necessary factor it makes sense to regard the effect as rebound. Another argument is that rebound sometimes just rides on unmet demand that might have been fulfilled (later) in other ways, such as through regular income growth. This does not seem a convincing argument though since the effect could be contained by a policy, as will be discussed later on.

4 Four Fundamental Reasons for the Rebound Phenomenon

In order to understand the nature of rebound effects and respond to them through management and public policy, one needs to understand their fundamental causes. For this purpose I intend to elaborate four views.

First, at a very general level, Alcott (2010) employs the famous $I = P * A * T$ equation (Ehrlich and Holdren 1971) to explain energy or environmental rebound effects. This equation represents environment impact (I) as being the product of three factors, namely population (P), affluence (A) and technological performance or efficiency (T). The latter factor captures increased efficiency, covering energy efficiency, which has the direct effect that it lowers I. However, P and A may change in response (indirect effects), which means the net effect on I is uncertain generally. Any right-hand side strategy or policy trying to reduce $T (or P, A)$ will therefore run the risk of rebound: reductions in one factor can be followed by compensatory increases in others. Alcott instead proposes implementing left-hand side or impact (I) caps which are independent of$P$, A and T. Examples are physical caps or taxes on carbon-based energy harvesting and mining or on pollutive emissions, and limiting energy consumption per person (quotas, rationing) as through personal carbon budgets. We will consider the best choice in more detail in Sect. 7.

Second, increased efficiency or conservation relieves limits that constrain the physical (energetic and material) dimensions of economies Alcott (2010). Limits relate to time, money, scarce resources, production factors, and space. By relieving such limits the physical dimensions of the economy can grow so that it can capture more, or even maximize use of, energy/materials. In an analogous way, ecosystems focus on maximizing energy capture (Schneider and Kay 1994).

A third view is based on recognizing the impact of improving the efficiency of general purpose technologies (Sorrell 2007, 2009). This results in the diffusion of such technologies which creates considerable economy-wide and dynamic effects, including growth of existing sectors, rise of new activities, processes and products, and associated emergence of demand and changes in consumer preferences. Technological history is full of examples, the steam engine being one: improvements in its efficiency gave rise to its diffusion to textiles, transport and many other sectors. The same happened with electricity, chemicals and currently computers and mobile ICT equipment. Another interesting technological characterization comes from Schurr (1985), who uses historical data to illustrate that the key to achieving overall or net energy conservation in combination with (muItifactor) productivity growth is to use technologies that are capable of more efficiently using all production inputs, not energy alone. More generally, it seems that energy efficiency improvements in technology are associated with three important rebound channels that other types of energy conservation (changing behavior) do not have: namely, direct rebound effects (more intense use because of a lower effective energy cost), diffusion of more efficient and therefore more attractive technologies, and general productivity effects. The latter covers increasing the productivity of other factors and relieving limits related to these as explained under the first view. Note that all three rebound effects are stronger for general purpose than other technologies.

A fourth view relates to bounded rationality of individuals, households and firms. This expresses itself through agents showing myopia, habits, biases regarding responses to uncertainty, and “wrong/mistaken” goals. Much has been written on this already in relation to the energy gap, that is, the problem of profitable energy saving opportunities not or insufficiently being translated into concrete energy conservation actions. However, this problem may extend to rebound, especially in relation to voluntary and purposeful energy conservation decisions made by consumers or producers. Since they cannot overlook all the consequences of their decisions, they cannot be sure that their net effect is a reduction in energy use. This is, arguably, a less important reason for rebound that the ones mentioned under the second and third views.

5 Empirical Estimates of Rebound

More research seems to have been devoted to energy rebound in relation to consumers/households than industry/firms. Nevertheless, much can be learned for industry from both the mechanisms and magnitudes of rebound as assessed in studies oriented towards consumers or households, since the basic energy saving strategies are similar, having to do with heating/cooling, transport, and use of electric equipment and other machinery (kinetic energy). Different types of studies (case studies, questionnaires, income/price-elasticity studies, statistical-econometric studies, general equilibrium modelling, etc.) offer distinct and possibly complementary angles.

A rigorous review by Sorrell (2007) provides a summary of the main rebound estimates, the assumptions and conditions under which they hold, and the shortcomings of the studies. The following empirical insights can be derived from it. Although there is much uncertainty about exact magnitudes, the available evidence shows that specific rebound effects or mechanisms vary widely between sectors and technologies. It is not possible to say whether direct rebound effects generally are larger or smaller than indirect effects. The direct rebound effect may be around 30% for many cases of household heating and cooling and lower for transport, although some studies report individual cases with much higher rebound rates. Indirect or economy-wide rebound effects may be around 10% while they often will be higher. Sorrell notes that various studies, notably applied general equilibrium analyses, report indirect rebound effects larger than 50%. These findings mostly concern developed countries: for developing countries the figures are likely to be higher, as argued in Sect. 1. A main reason is that rebound effects will typically be greater when the cost of energy is large compared to total costs or income. The latter suggests that rebound effects will differ between technologies, sectors and even countries (developed versus developing) in relation to energy/total cost ratios. In other words, sectors and services in which the production factor energy is relatively important are likely to show higher rebound effects in response to energy conservation efforts, ceteris paribus. With regard to countries, unmet demand for energy services in developing countries suggests a higher potential for rebound here. A global model analysis by Barker et al. (2009) estimates that energy conservation efforts in transport, buildings and industry for the period 2013–2030 have to count on a global rebound effect of more than 50% by 2030, of which 10% is a direct effect and the remainder indirect and economy-wide effects.

A caveat to all these results is that the empirical evidence is based on relatively few studies, few comparable studies and debatable models and data. Sorrell (2007) and various other authors think that the empirical evidence is too weak to draw definite conclusions about the magnitude of rebound effects. For example, some studies find very high effects: e.g., Hanley et al. (2009) find that a general improvement in the energy efficiency of production sectors of the Scottish economy generates backfire; and Frondel et al. (2008) assess fuel-efficiency improvements to cause 57–67% rebound. In addition, several studies find relatively small rebound effects, in the range of 10–20% (Schipper and Grubb 2000; Greening et al. 2000; Small and Van Dender 2007). However, as will be discussed in the next section, these results need to be interpreted with care, as they are likely to be partial in many ways. A logical question is why studies provide such diverse estimates for the magnitude of rebound effects:

Table 1 Qualitative assessment of indicators of potential rebound for different energy-consuming activities in industry

Type of industrial energy-consuming activity	Proportion of energy use	Energy conservation with and without efficiency improvement	Energy efficiency improvement		
		Energy/total cost ratio	More intensive use of current equipment (direct rebound effect)	Productivity effect (effect on other production factors)	Technological diffusion effect (esp. general purpose technology)
Industrial lighting	Small	Small	Medium	Small	No
Refrigerating	Medium	Small	Small	Small	No
Air conditioning	Medium	Medium	Small	Small	Small
Space heating	Medium	Large	Small	Small	No
Water heating	Medium	Small	Small	Small	No
Industrial processing	Large	Large	Medium	Large	Medium
Transport and logistics	Large	Large	Large	Medium	Medium

Activities like energy (electricity, oil, gas) generation, transformation and transport, and electric motors might also be included

is this because of unique local, case study features or because of methodological differences? Probably both factors play a role.

Table 1 shows indications of aggregate categories of energy-consuming activity in industry that allow a qualitative estimation of rebound effects of energy conservation. From the rebound mechanisms listed in Sect. 3 we can derive that important features to assess the potential rebound effect are the energy/total cost ratio, direct rebound effect (more intensive use of current equipment), productivity effect (or effect on other production factors), and technological diffusion effect. From the table it follows that most rebounds are likely to be associated with the activities industrial processing and transport/logistics.

6 Uncertainty About Empirical Estimates: A Lower Bound to Rebound?

There is not much disagreement that rebound is possible and likely. But there is debate over its magnitude. Various studies summarize the debate (e.g., http://www.eoearth.org/article/Rebound_effect). The relevance of policy to contain or reduce rebound effects is clear, irrespective of the precise magnitude of rebound. Nevertheless, it is interesting to know whether rebound is small (0–20%), significant (20–50%) or worrisome large (more than 50%) or even counterproductive (more than 100%, or "backfire"). Current empirical research cannot settle this entirely, even though methodologically rigorous studies have estimated backfire for particular cases (e.g., Hanley et al. 2009).

Various authors argue that there are many reasons to believe, first, that an accurate estimation of rebound is very hard, and second, that many empirical studies of rebound have produced estimates that very likely underestimate the real effect, since upward biases are more noteworthy than downward ones (Polimeni et al. 2008; Sorrell 2007, 2009). To support this view, partial analysis, unclear system boundaries, uncertain and unobservable cause-effects chains, limited time horizons, neglect of international dimensions (transboundary effects, trade, relocation), and of long term dynamics (changing, endogenous preferences, technological change and diffusion, new products, capital accumulation and economic growth) are relevant. Many empirical studies of energy conservation and rebound depend heavily on price elasticity estimates. However, these reflect very partial and temporary indicators of behavioral responses to energy cost changes. The magnitude for most rebound mechanisms identified in Sect. 3 is hard to assess empirically. In particular, it is difficult to trace or prove the exact causality underlying certain mechanisms—decision makers themselves may not even be aware of it.

Polimeni and Polimeni (2006) and Polimeni et al. (2008) emphasize that system boundaries are not fixed but continuously change as part of the almost inevitable, evolutionary drive of the system to capture more energy, to expand and to create new pathways of energy, through innovation and creation of new technologies, products, services and even preferences and sectors. Herring (2008) refers in this context to “transformation effects”. Any reduction of energy use somewhere in the system will mean more available energy which will be captured somehow—similar to what is widely documented to happen with natural, ecological systems. To fully understand this point one needs to dive into the difficult considerations of thermodynamics of living systems (Schneider and Kay 1994). In this context, Ruzzenenti and Basosi (2008) emphasize the trend of an increase in the overall complexity of production which is characterized by more roundabout processes and outsourcing, and which in turn gives rise to a steady increase in freight transport and associated energy use.

Some authors have claimed a rebound at the macro or global level of more than 100%, also known as the Jevon’s paradox (after Jevons 1865 analysis of consumption and prices of coal) or “backfire” effect. A fierce position on this was taken in a recent book by Polimeni et al. (2008). However, it does not really offer a systems analysis but rather ad hoc examples. As a result, correlation may be confused with causality, in particular income growth and technological diffusion may be attributed too much too improvements in energy efficiency rather than be recognized as autonomous phenomena.

Another factor contributing to uncertainty about total rebound effects is the precise role of energy in production, notably the degree of substitutability of energy by other production factors, the energy (exergy) embodied in non-energy factors—labor, capital, materials and (productive) land, and the effect of improvements in the productivity of capital, labor and materials due to energy efficiency improvements. Ayres and Warr (2005, 2009) argue for a different view than of mainstream economics, notably growth theory. They show that with an appropriate exergy measure historical economic growth of the USA can be much better replicated than with more standard economic growth models that include some form of technological change or learning (of course one may be an imperfect proxy for the other). Ayres and Warr further provide evidence for the idea that the marginal productivity of energy inputs may be considerably larger than their cost share. This means that improving energy efficiency would generate a larger output effect than is recognized by traditional economic models. This indicates the relevance of the theme of the role of energy in production for the study of rebound. The fact that this theme is debated (or neglected) and serious studies of it are scarce implies additional uncertainty about the potential magnitude of energy rebound.

Other uncertainties or at least difficulties in assessment of rebound effects relate to capital costs and embodied energy of more energy-efficient equipment. With regard to the first issue, improved technology generally is more expensive (in terms of investment/capital cost and sometimes also in terms of operation costs or input of other factors), in which case the direct (intensified use) and re-spending effects will be smaller (Henly et al. 1988; Sorrell and Dimitropoulos 2007). Embodied energy contributes to enlarge the rebound effect. However, its assessment requires taking into account all indirect use of energy throughout the economy, ideally using a perfect I/O table. In summary, although biases in estimating rebound can go either way, it is most likely that rebound is underestimated.

7 Policy Responses to Energy Rebound

At first sight, voluntary energy conservation, i.e. not stimulated by environmental regulation raising energy prices, seems an easy, cheap solution to energy-related environmental problems like climate change. That is precisely why it receives so much political support—from the left to the right of the political spectrum. However, voluntary energy conservation will run a serious risk of generating large rebound effects due to lack of any (additional) physical and price constraints on behavior. Even though the magnitude of rebound is uncertain, the high likelihood that it often will be positive is sufficient reason for trying to reduce it or, better, to optimize (not minimize) social welfare that includes environmental externalities associated with energy use and takes account of rebound effects. The starting point for the analysis here is the set of fundamental reasons for rebound as discussed in Sect. 4. An important principle should be to make sure that energy conservation does not unnecessarily relieve limits—physical, time or financial—at both individual and systems levels. To realize this, policies need to integrate incentives for energy conservation and limitation of rebound. This might be realized by a mixture of policy instruments or by a single instrument like tradable permits which can set a cost-effective ceiling to total energy use or (better) its environmental impact (like CO_2 emissions). This section will address the question which advantages and disadvantages from the perspective of rebound are associated with the various instruments available to environmental policy makers.

To take a robust starting point for policy analysis, let us consider a common typology of instruments to stimulate energy conservation: (i) information provision and “moral suasion” (fostering “voluntary action”), (ii) direct or physical regulations (standards for technology or buildings), (iii) price regulation (taxes, levies), (iv) subsidizing energy conservation, and (v) tradable permits (i.e. an overall ceiling combined with a price mechanism). There are two shortcomings associated with the instruments (i) and (ii). First, they do not raise costs of energy use per unit (instrument (i)) or very limitedly (instrument (ii)), so that the rebound effects of energy conservation or improved energy efficiency occurring through more intensive use of current equipment and re-spending of associated money savings will be considerable. Second, they do not impose a ceiling on total energy use, which means that productivity effects, new preferences, technological diffusion and income growth give rise to more consumption of energy services. A recent example of instrument (ii) is the abolishment of incandescent light bulbs set in motion by the EU—which can against the background just sketched be judged as good intentions but possibly ineffective policy, that is, if it is not complemented by higher prices of energy (electricity). Such a policy is likely to result in more intensive use of light services (more lamps as well as more light hours) and re-spending of direct monetary savings associated with more efficient lighting systems. It even has been suggested that in Nordic countries the replacement of classic light bulbs, which produce relatively much heat, will lead to more energy use by home and office heating systems to substitute for heat loss, notably during cold periods which are extensive here. In addition, a practical problem of technical (emission or quality) standards is that each technology, prod-

Table 2 Impact of policy instruments on rebound

Instrument type	Smaller rebound effects	
	Affected by cost per unit of energy use: Resulting in less intense use (or a smaller increase in the intensity of use) of equipment, lower re-spending effect and less shifting to other energy-using products and services	Affected by hard limits to overall energy use (or GHG emissions): Limiting the effects of increased productivity, new preferences and diffusion of technology effects on total energy use
Information provision and "moral suasion"	No	No
Command-and-control (direct/physical regulation or technological/emission standards)	No	No
Market-based instruments or price regulation (taxes, levies)	Yes	No
Subsidizing energy conservation	No	No
Tradable permits (i.e. an overall ceiling combined with a price mechanism)	Yes	Yes

uct and service needs its particular piece of information, otherwise rebound will also involve shifts to products and technologies which fall outside the regulatory framework.

With regard to instrument (iii), price regulation through environmental or energy taxes or levies, the first problem does not exist as the costs of energy use are raised. But the second problem, i.e. a lack of a ceiling to energy use, still is relevant, even though because of the higher energy cost it will be less severe than in the case of instruments (i) and (ii). Instrument (iv), subsidizing energy-efficiency improvements or conservation (i.e. "the polluter is paid"), will even more strongly stimulate rebound than instrument (i), as spending power of energy users (polluters) increases. Generally, one should be very careful with direct and indirect (hidden) subsidies anyway if there is no clear problem like positive externalities or knowledge spillovers in R&D or innovation that needs a resolution. The stimulating impact of subsidies on rebound due to an enlargement of energy-using activities means an extra reason to be careful with this instrument (van Beers and van den Bergh 2009). Only with instrument (v), tradable permits, both aspects of raising the cost of energy use per unit and imposing a ceiling to total energy use can be arranged. This makes it the most suitable instrument to limit rebound, as will be explained in detail below. This all is summarized in Table 2.

If instrument (iv), i.e. tradable permits on energy use or CO_2 emissions, are introduced, preferences and technologies can change in any direction in response to energy conservation. However, if this means an increase in the potential demand for energy services (or CO_2 emissions), then because of the fixed supply, that is, the ceiling to total energy use or CO_2 emissions, scarcity will increase and the price of permits and therefore of energy will go up to the extent that the demand for energy services will remain within the limits set by the ceiling. No other instrument can realize this. Studies comparing CO_2 taxes with tradable permits conclude in favor of the one or the other, depending on the criteria taken into account (efficiency, cost-effectiveness, distribution, uncertainty about costs and benefits, monitoring/control costs, technical innovation potential, risk of technical lock-in). Subtle comparisons show that the two instruments share many features, and that hybrid systems can do the job as well and perhaps better (Parry and Pizer 2007). However, no comparison so far has taken the rebound effect into account as an evaluation criterion. If this is done, then tradable permits come out as a superior instrument of energy conservation or climate policy. However, an alternative solution is offered by Sorrell (2007): "Carbon/energy pricing needs to increase over time at a rate sufficient to accommodate both income growth and rebound effects, simply to prevent carbon emissions from increasing. It needs to increase more rapidly if emissions are to be reduced." The disadvantage of such a policy arrangement is that governments need to collect continuously information about relevant changes in the economy and adapt the policy in response, which is bound to meet a great deal of political and social resistance. As opposed, a once-and-for-all installed tradable permit system, if implemented well, can do the job more easily, with an endogenous price responding automatically to market (technological and preference) changes.

A few other remarks on the intent of rebound policy are in order. In Sects. 3 and 4 it was concluded that energy efficiency improvements in technology are associated with two important rebound channels that other types of energy conservation (changing behavior) do not have: namely, direct rebound effects and diffusion of more efficient technologies. One should thus be very careful in stimulating more energy-efficient equipment—its net effects on energy use could be disappointing or even negative. This further suggests that energy conservation policy might want to focus its attention on energy conservation strategies that change behavior rather than technology. In line with this, policy could try to motivate decisions, particularly re-spending ones, to be directed at (relatively) energy-extensive goods and services. This holds equally for consumers and firms. The obvious instrument is one that can signal accurately the energy intensity of goods and services to buyers. Price corrections to account for energy (or better even CO_2 and other externality-causing substances) are best capable of this, and thus come out as the superior instrument, whether in the form of taxes or tradable permits.

Of course the previous conclusion does not mean that one should avoid improvements in technical efficiency. But one needs to realize that many of these will have negative net effects, especially when they concern core or general purpose (GP) technologies which tend to permeate the economy once a threshold efficiency of operation is realized, and thus indirectly contribute to growth of energy services. Pragmatically, policy should distinguish clearly between GP technologies and technologies that can realize a net conservation benefit. Sorrell (2007) emphasizes the case of insulation, but it is not clear that there are many examples around. The problem may be that when technologies do not have a general purpose character, associated innovation (RDD&D) costs may be relatively high as each specific technology with a limited area of application will require its own R&D and learning path. So it seems there is no solution without disadvantages.

Policy makers should finally realize that a potential paradox follows from the discussion of Sect. 3, namely that rebound is large where energy use and thus potential savings are large, and that rebound is small where energy use is modest and likewise potential savings are small. The foregoing remarks imply a serious warning against being overly optimistic about what one can realize with energy conservation that is not regulated well by combined price-quantity regulation (i.e. tradable permits). The ultimate contribution of energy conservation might be more disappointing than many are willing to accept. Taking rebound seriously, means making energy conservation strategies more effective. This will have to include also a serious evaluation of the net effect of energy conservation programs and a comparison of these with alternative strategies, notably stimulation of, or investment in, renewable energy.

8 Conclusions

Despite good intentions of governments, firms and individuals stimulating or undertaking energy conservation, such efforts offer no guarantee for effective reduction of energy use and associated greenhouse gas emissions. One message of this article is, therefore: don't get fooled by good intentions. Most studies concluding in favor of energy conservation are based in partial analysis and thus tend to arrive at overly optimist conclusions regarding the environmental and welfare impacts of related strategies.

Fourteen possible rebound channels or mechanisms have been defined here. It was argued that indirect compensatory effects of energy and environmental strategies and policies are not the exception but the rule. While many existing empirical studies find positive to very high rebound, several even more than 100% (backfire), all studies are incomplete and partial in system, space and temporal senses. This means that they tend to underestimate the total rebound effect.

Four fundamental reasons for the rebound effect have been mentioned. First, very generally, the famous $I = P * A * T$ equation suggests that population (P), affluence (A) and technological performance or efficiency (T) are not independent factors. In particular, P and A may change in response to improved energy efficiency, a subcategory of T. Second, increased energy efficiency relieve physical, money and time limits that in turn allow an increase in the energetic and material dimensions of economies. Third, improved energy-efficiency of general purpose technologies stimulates their diffusion, which creates economy-wide and dynamic effects. Fourth, bounded rationality of individuals, households and firms means they cannot overlook all the consequences of their energy conservation decisions. The latter reason is probably less important than the second and third.

There are various reasons to believe that energy rebound can be a serious problem for developing countries. The main reason is that consumption of energy services by both industries and households is much less saturated than in developed countries. Energy efficiency has a double role in developing countries, namely contributing to development and to reduction of pollutive emissions. Although these goals may seem conflicting they are not. For if rebound is controlled, development will not excessively harm environment, and indirectly—through externalities—welfare.

A practical advice is to undertake an "energy/environmental rebound assessment" of important energy conservation projects or strategies, just like any large investment project requires an environmental impact assessment. Given that a thorough rebound assessment will be expensive and difficult, and its results would still be uncertain, one might aim for at least a qualitative assessment of the important types of rebound from the list of mechanisms presented in Sect. 2.

Policy evaluation for energy conservation should include the rebound effect as an evaluation criterion. If this is done, then—as discussed in the previous section—tradable permits come out as a superior instrument of energy conservation annex climate or CO_2 mitigation policy. Energy conservation can only be effective after a policy has been put in place to secure environmental regulation (pricing environmental externalities). As argued here, containing rebound in addition requires setting a ceiling to energy use or better undesirable emissions like of CO_2. The ideal instrument which follows from the two conditions is a system of tradable permits.

Energy efficiency improvements or more generally energy conservation should not be a stand-alone or direct goal of policy. The literature on energy rebound makes very clear that energy conservation (policy) is no substitute for environmental regulation, much the same as environmental innovation (policy) is no substitute for environmental regulation. We have to recognize that private firms, consumers and politicians alike will always search for an easy way out. This means they will try to focus on solutions that seem cheap. Unfortunately, as the policy evaluation section showed, the easier and cheaper the solution seems, the more likely rebound tends to be.

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