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Energy rebound and economic growth: A review of the main issues and research needs ☆

R. Madlener [a,*], B. Alcott [b]

[a] Institute for Future Energy Consumer Needs and Behavior (FCN), Faculty of Business and Economics/E.ON Energy Research Center, RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany
[b] Gretenweg 4, 8038 Zurich, Switzerland

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ABSTRACT

Contrary to conventional wisdom, more efficient use of energy may actually through rebound effects lead to greater instead of less total consumption of energy—or at least to no diminution of energy consumption. If so, energy efficiency strategies may serve goals of raising economic growth and affluence, but as an environmental or energy policy strategy could backfire, leading to more resource use in absolute terms rather than less. This, in turn, could in the long run hamper economic growth, for instance if resource scarcity crowds out technical change. The hypothesis that rebound is greater than unity ('backfire') predicts the observed real-world correlation between rising energy consumption and rising efficiency of energy services, however difficult it may be to define a precise holistic metric for the latter. The opposing hypothesis, i.e. that rebound is less than unity and that energy efficiency increases therefore result in less energy consumption than before, requires on the other hand strong forces that do account for the empirically observed economic growth. This paper summarises some of the discussions around the rebound effect, puts it into perspective to economic growth, and provides some insights at the end that can guide future empirical research on the rebound topic.

1. The economic consequences of energy efficiency change

In order to slow down the depletion of non-renewable energy sources and to reduce emissions from the combustion of fossil fuels, policies are often propagated that aim at increasing the energy efficiency of production processes. The claim that energy efficiency increases necessarily lead to reduced energy consumption has been questioned, as has the notion that such increases will always have a positive impact on economic growth. Obviously, the discussion presented here for the case of energy could easily be extended to other resources that are the target of conservation policies (e.g. water).

This paper investigates the relationship between changes in energy efficiency and total energy consumption of an individual entity (firm, household) and a collective economic entity (economic sector, national or world economy). Is there a causal connection? While some rebound effect is universally agreed to follow efficiency increases, is the size of this *total rebound* large enough to speak against efficiency as a resource-saving strategy? Note that our dependent variable—the amount or quantity of energy used—is often taken as the explanatory or independent variable, correlated with growth of GDP, to address an entirely different question, viz. to explain growth [1–3]. Here, we are interested in the role of technical change and the substitutability between goods and services in shaping the relationships between energy consumption and energy efficiency (or rebound), energy efficiency (or rebound) and economic growth, and economic growth and energy consumption, respectively. Fig. 1 depicts the three dimensions considered in our rebound discussion, all of which are affected in important and often ambiguous ways by technical change and the substitutability of input factors of production.

One argument combining efficiency, energy consumption and GDP growth is for instance that increased efficiency in the use of energy inputs contributes to economic growth and since this, in turn, implies greater energy consumption, then efficiency itself implies some increase of energy consumption [4]. Yet if 'dematerialisation' obtains, then some net decrease of energy consumption could occur.

1.1. Some definitions

Before entering the discussion any further it is useful to define some of the terms used. *Engineering savings* is a theoretical

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* Corresponding author. Tel.: +49 241 80 97 162; fax: +49 241 80 92 206.
E-mail address: rmadlener@eonerc.rwth-aachen.de (R. Madlener).

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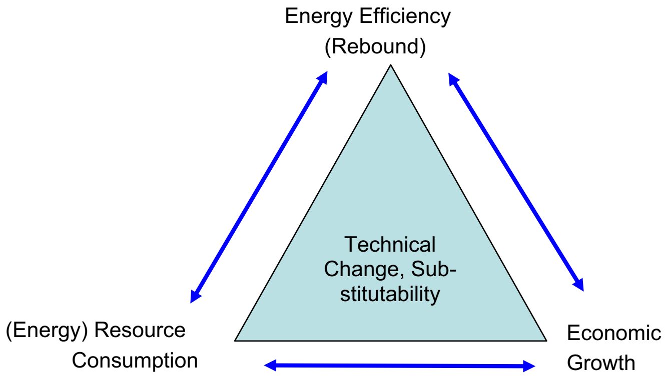

Fig. 1. Dimensions considered for the discussion of energy rebound and economic growth.

quantity of energy that could be saved after a certain increase in energy efficiency, if the quantity of goods and services demanded or consumed were held constant. As light bulbs, cars and steel-making machinery use less and less energy input per output (e.g. lumens/m^2, tonne-kilometres or tonnes of steel), respectively, we could—from a conservationist's perspective—deliberately opt to produce and consume no more of these outputs, or indeed other outputs, yielding real 'calculated' savings in energy in any given time period.

Rebound is the additional energy consumption enabled by energy efficiency increases, i.e. after energy input per unit of output has gone down, and provided the efficiency increase implicitly led to a reduction in the price of producing the output. We can afford to buy more energy-using outputs if costs per unit of output have fallen, resulting in an *income effect*: after enjoying our usual quantities of light, car travel and steel our budget is not used up; the quantities to consume have become cheaper per unit, and we can buy more of the same products, or other products, which also require energy inputs for their production and consumption. Because the *relative* prices of lighting, car- (actually tonne-) kilometres and steel have fallen there is also a *substitution effect:* all other things being equal, we will consume more of those goods and services that are now produced in a more energy-efficient way. Finally, if the initially lowered demand for energy inputs—holding production and consumption quantities constant—leads to a fall in the unit price of energy, a general *price effect* leads to the substitution of energy for other factors of production. In other words, the energy efficiency increase can also be regarded as an outward shift in the production possibilities frontier (i.e. a higher output can be achieved with the same input or, conversely, less input is needed for the same output level). The energy 'freed' from producing the previous level of output of goods and services is available, at no higher cost, for some additional production.

A few points are worth noting here. First, consumer preferences may also change due to improvements in energy efficiency, such that demand shifts to higher levels of comfort, or other quality attributes. Second, we may decide to substitute energy for time (using faster means of transport, eating more fast food, etc.). Third, changes in the capital costs of energy-related services have an important influence on the size of the rebound effect, and capital grants paid by government may actually inflate the rebound effect, as consumers do not have to bear the full cost of the purchase decision [cf. 13, pp. 6–7]. Fourth, we are only concerned here with technical change that affects energy efficiency, i.e. with energy rebound.

Rebound is commonly measured as a percentage of engineering savings; if it is greater than 100% this is usually referred to as *backfire*, so named because the modern discussion of rebound begun by Brookes [5,6] and Khazzoom [7] asked whether newly enacted government policies to save energy through efficiency caused real energy savings, or—because of rebound greater than unity—might actually 'backfire'. If backfire exists, this would result in more energy consumption than before the (policy-induced) increase in energy efficiency. The 19th-century discussion of this paradox started and also ended with William Stanley Jevons' book *The Coal Question*, which expounded the backfire position [8,9]. This 'Jevons' paradox' is of course not to be confused with the 'energy paradox', the latter of which is related to the high implicit discount rates found empirically for many energy efficiency investments, and which attests the fact that economic actors often do not invest in energy efficiency measures or technologies, even though it appears to be in their economic interest to do so (seemingly irrational behaviour).

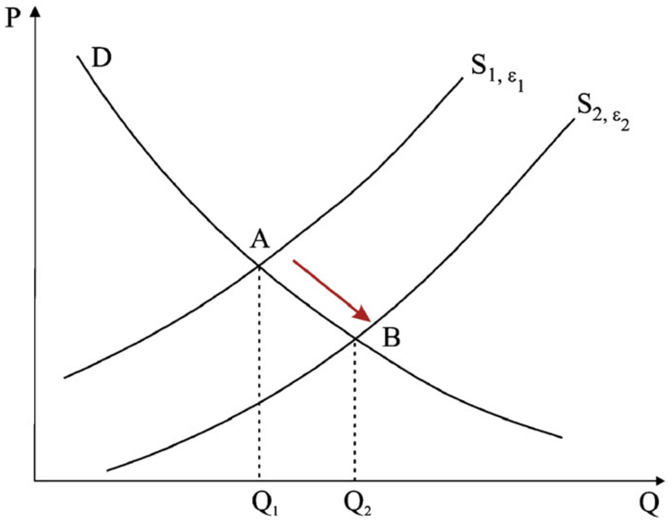

Fig. 2. Lower input factor costs due to an efficiency increase by $\Delta\varepsilon$ enable an outward shift in the supply function. *Source*: [7], modified.

1.2. *Shift of the supply curve*

Khazzoom [7] described the increase in output offered at a given price level that is caused by efficiency-induced cost reductions (shift of the supply curve S to the right, due to an increase in efficiency from ε_1 to ε_2). This results, *ceteris paribus*, in greater demand Q_2 at the new equilibrium point B for the more efficiently-produced goods and services than before at demand Q_1 (in equilibrium A; see Fig. 2).

Since of course energy input *per unit* of economic output has fallen, demand for energy inputs does not necessarily rise above its previous level (backfire), but Khazzoom's point was that real savings *must* be lower than engineering savings. In his opinion calculations that are based on the engineering facts alone "… overlook the fact that changes in [e.g.] appliance efficiency have a price content." [7, pp. 21–22]. For further rigorous statements and definitions of rebound see, e.g., Wirl [10, p. 31], Birol and Keppler [11, pp. 460–463], Schipper and Grubb [12, pp. 369–370], Binswanger [13, p. 120], Sorrel and Dimitropoulos [14], and the synopsis provided in Herring [15] and Herring and Roy [16].

1.3. *Taxonomy*

When consuming the previous quantity of output after a cost-neutral energy efficiency increase, some unused purchasing power thus remains, i.e. is freed for additional consumption.

This is an *economy-wide rebound effect*, already attested by Jean-Baptiste Say more than 200 years ago:

> But whence is derived this […] larger supply of wealth, that nobody pays for? From the increased command acquired by human intelligence over the productive powers and agents presented gratuitously by nature […]. A power […] before known and available is directed with superior skill and effect, as in the case of every improvement in mechanism, whereby human or animal power is assisted or expanded [17, p. 101].

We have counted some 28 different terms for rebound effects in the literature. While we accept the basic classification into *income*, *substitution and price effects*, we further categorise the new 'rebound' demand as follows:

1. by the same consumer for the same product or service;
2. by the same consumer for a different product or service;
3. by a different consumer for the same product or service;
4. by a different consumer for a different product or service.

A fifth category is the case of consumers' choosing leisure instead of additional consumption, reducing their purchasing power (e.g. by working less) to a degree proportional to engineering energy savings. Here rebound would be zero (if macroeconomic effects of leisure can indeed be neglected), and the efficiency increases have enabled real resource savings with no loss of affluence.

The literature separates this demand into 'direct' (roughly, categories 1 and 3) and 'indirect' rebound (categories 2 and 4), together constituting 'economy-wide' or simply 'total' rebound (e.g. [16, p. 196]). A special problem is presented by *new products or services* or whole new industries, e.g. railroads in the 19th century or lasers in the 20th century, that are partially enabled by efficiency increases in extant products and industries [8,18,19], but for simplicity we ignore these here. Note that category five is always possible, i.e. were all humans to 'reap' energy efficiency benefits in the form of less work and less purchasing power, rather than greater consumption, this would lead to a 100% realisation of the potential (or theoretical quantity) engineering savings. A zero price elasticity of demand would describe this situation. Human history, psychology and poverty indicate that this is very unlikely. Given any positive value of the elasticity, rebound must thus be greater than zero.

2. Various approaches

How can one go about answering the question of whether total energy consumption ends up less, greater, or the same due to energy efficiency increases? We identify four different approaches here that can be used.

2.1. Economic/technological history

Jevons [8] rendered it at least plausible that without the efficiency increases in steam engines and metal smelting the demand for coal could never have reached mid-19th-century levels. That is, if we assume that energy technology had remained at efficiency levels of, say, the year 1800, how much (increase in) annual energy consumption is imaginable now, 200 years later? Rosenberg sums up this argument for the plausibility of backfire as follows:

> The Bessemer process was one of the most fuel-saving innovations in the history of metallurgy. However, the innovation made it possible to employ steel in a wide variety of uses that were not feasible before Bessemer, bringing with it large increases in the demand for steel. As a result, although the Bessemer process sharply reduced fuel requirements per unit of output [a *ratio*], its ultimate effect [seen from an economic, not just an engineering, perspective] was to increase, not to reduce, demand for fuel [18, p. 166; additions in square brackets by the authors].

Neither should one neglect the perhaps special case of the history of efficiency improvements in obtaining energy, known as the *energy return on* (*energy*) *investment*, or shortly EROI. [1] Without these increases, some law of diminishing returns—deeper mines and drill-holes, for instance—would have rendered energy more and more expensive rather than ever-cheaper, as has been the case. Related to the gradual improvement of technology over time are the two phenomena 'lock-in' and 'path-dependency' [20,21], respectively, both of which explain part of the more general issue of drag or inertia imposed on the turnover of the capital stock. Note, however, that the replacement rate of old against new capital stock as well as EROI are usually not part of the discussion about the size of rebound effects, since the two relevant measures for the assessment are (1) changes in the technical efficiency with which particular goods and/or services are provided and (2) total consumption levels.

2.2. Microeconomic aspects

Applying the microeconomic approach analysing prices, substitution and income effects, numerous empirical studies have investigated *direct rebound* (additional demand for a good or service that can be more efficiently produced with the new technology). For instance, after buying an energy-efficient Toyota Prius automobile, do people then either buy or keep additional cars, and does the weight of the household's entire car fleet perhaps increase [22]? One could also ask whether a more energy-efficient car is driven more than the previous one [23]. Studies in the UK attest, for instance, that after a house is insulated or obtains a more efficient space-heating system, people do tend to heat more (i.e. higher temperatures or additional, previously unheated rooms) [24]. A useful survey of such direct rebound studies can be found in [25], from where it can be learned that direct rebound effects identified were in the order of 10–30% (0–50%) for residential space heating (cooling), <10–40% for residential water heating, 5–12% for lighting, 0% for residential appliances, and 10–30% for automobiles, 0–2% for firm's lighting, and 0–20% for firm's process uses. It is worth mentioning that a reduction in the cost of any good or service due to energy efficiency increases also has an important bearing on marginal consumers, i.e. those that could not previously afford the energy service concerned.

Microeconomics illustrates why this topic is still a paradox: if driving a kilometre in a car with a more energy-efficient engine leaves unused budget, perhaps we buy more 'driven kilometres'. But since petrol inputs are only part of the costs of driving a kilometre, and since each kilometre is driven more efficiently, the new demand *for petrol* would seem to necessarily be lower than that saved in driving the customary number of kilometres [26]. However, a construct or measure such as a 'driven kilometre' is rather artificial, and we must also examine the induced substitution and price effects, as well as take the embedded energy and capital costs of the change to greater efficiency of the capital stock into account (note that we abstract from changes in labour input and quality or comfort here, and only consider energy and capital inputs). In microeconomic terms, the size of rebound depends upon the *efficiency elasticity of demand* for energy [27], a compound which can be broken down into the efficiency elasticity of energy price times the price elasticity of energy demand.

The viability of this approach would be enhanced by fulfilling two conditions: First, the system boundaries of empirical studies must be expanded to world scale; since many energy markets and emissions are international, and since embedded energy and material are increasingly traded globally, country or OECD studies alone are insufficient for a complete picture [28–30]. Second, the goal must be to measure *total rebound*, i.e. indirect as well as direct effects: the increased 'purchasing power' of the budget can be used to purchase any products whatsoever, and can be shared by people who were previously not in the market at all. The rebound from more efficient automobile motors can just as well be additional demand for air travel. Tracing indirect effects with the tools of microeconomics, however, proves to be extremely difficult [26,31]. Moreover, estimates of total rebound vary wildly. For instance, while for the UK 4CMR [32] arrives at a figure of 26% and Allan et al. [33] closer to 40%, for others it is clear that backfire might be the case [8,34,35]. On whether rebound is greater or less than unity, the jury is still out.

2.3. Macroeconomic aspects

With statistical methods one could test the hypothesis that, in aggregate and over time, technological efficiency increase is a net contributor to the size of energy consumption and its growth. The long-term increase of energy consumption needs no documentation. On the other hand, although few doubt it, are we so sure that energy efficiency has increased also if measured with physical metrics? How, indeed, can we measure changes in energy efficiency in the aggregate non-monetarily [36]?

Jevons [8] was the first writer to show that large and obvious energy efficiency increases were accompanied by energy consumption increases; he traced efficiency increases in steam engines and steel (or pig-iron) production, then compiled statistics on coal consumption. Greenhalgh [28] shows engineering efficiency gains of over 20% for household appliances in Denmark between 1977 and 1986, alongside rising electricity consumption. Rudin [37] does the same for US energy use in commercial buildings (8% more efficient from 1979 to 1995) and cars (30% from 1967 to 1997). Smil [38], likewise, analysed changes in energy efficiency with changes in energy consumption (also [39]). Recently, Herring [15] maintains a (positive) causal relationship between lighting efficiency and electricity consumption. In aggregate terms for the US economy during the entire 20th century [4, pp. 340 and 351] show a strong correlation between technical efficiency increase and exergy consumption.

However, correlation is not causality, and for testing the hypothesis rigorously it would be ideal to have a metric for energy efficiency levels that is valid in different time periods and in different countries (or at different scales). But again, given the global nature of many environmental problems (e.g. climate change) and the global nature of the market for fossil fuels, for a more comprehensive assessment and understanding of rebound effects we need to study world statistics as well. Second-best would be metrics for well-defined products, industries or sectors, whose efficiency change could be measured in percentages, and then some average for the whole world economy calculated. Recent work by Ayres and associates [4,40,45] makes important strides in measuring efficiency changes in terms of exergy and work at point of use, yet it remains difficult to measure aggregate global output as physical work, heating, endothermic change, lighting and produced electricity.

To measure both 'economic growth' and 'output' as the numerator in input–output efficiency (or as denominator for energy 'intensity'), one must decide between financial, utility or welfare, and physical metrics. Taking GDP as the metric—i.e. economic output in monetary terms divided by energy input—has many disadvantages. It is well known that GDP fails to measure many economic activities, ranging from unpaid work to bartered goods, and also resource depletion and loss of environmental services [41] where the true costs are not reflected in the price. Moreover, the prices of the goods that GDP counts are also influenced by factors not pertaining to changes in efficiency and costs of production, but rather consumer tastes, quality changes, and even politics [38,42,43].

Taking human utility—or welfare, or services—as the quantity against which energy inputs are measured also has problems. For instance, if a second person rides in a car, utility is virtually doubled while energy input stays virtually the same. But this is not a *technological* efficiency change, although it is often regarded as a measure of something like economy-wide energy efficiency or productivity. Welfare, too, is subject to many influences. The energy efficiency policies we wish to scrutinise, however, typically involve energy inputs compared with some *physical*, environmentally relevant output, like lumens per m^2, tonne-kilometres or tonnes of steel.

To find a physical metric has proven difficult. Even on the input side, is it rigorous enough to measure inputs of *energy* in tonnes or Joules of different kinds of oil or petrol, of coal, or of natural gas? Or should we measure instead *exergy* inputs [44]? Ayres and Warr [45], for instance, refer to an exergy/energy ratio, i.e. the conversion of useful energy to useful work. But since work is understood in terms of energy, how do we distinguish between an input and an output Joule of exergy? And since exergy is energy of higher quality, or greater availability to do work, what are the inputs into the 'transformation' process increasing this quality, or is it simply meant to describe, for instance, low-entropy petrol as opposed to high-entropy crude oil?

On the output side, can the weight (or mass) of consumable and durable goods, including the (energy-using) stock of capital goods actually doing the work, serve as an aggregate metric? Radetzki and Tilton [46] consider this, but because of qualitative differences in products find it necessary to 'weight' these weights. Among others, Dahlström and Ekins [29] attempt to weight physical characteristics—e.g. chemical elements, weight, waste, shape, and recycled tonnage—by economic value, attempting to integrate traditional material flow analysis with value chain analysis. But here the danger of conflating physical and subjective economic characteristics is very great (see also [47,48]). The quest for an all-encompassing, purely physical measure of efficiency is a precondition for rigorous statistical analysis, but seems still far off in current research.

A further element largely ignored in discussions on the size of energy rebound effects is time. In many situations it has economic value if goods or services can be provided in less time. As an example, if we extract from the same amount of energy the same amount of useful work in a shorter time span, we create some additional value. With some exceptions (e.g. [13]), most rebound assessments, however, remain silent about this time value of energy (work over time equals power), and only address work over energy. Since, however, the time freed by the *energy* efficiency increase is available for further production and consumption, thus of course increasing economic growth, the entailed additional energy consumption must be booked under rebound. (The same argument can be put forward for exergy considerations.)

2.4. Economic growth theory

Early economic growth models incorporating technical change as an exogenous factor attempt to explain the role of technical change for sustained growth by “manna from heaven” [49]. Growth models including energy and material alongside capital and labour reduced the statistical residual significantly [1,50].

Newer research has accounted for this very large ‘technical change’ residual in the earlier studies by means of a KLEC production function (capital, labour, energy and creativity). By including both amounts of energy and our creativity in using energy more efficiently, not only is product ion output much more fully explained but it is also shown that energy’s contribution to product ion output far exceeds that of its share in the monetary value of inputs as represented in the national accounts [51].

Energy efficiency, as part of the technical progress in neo-classical growth theory, is conventionally seen as a driver of economic growth. A commonly found argument in standard growth theory literature is that technical change and factor substitution can effectively de-couple economic growth from the demand for resources and environmental services, i.e. raise ‘efficiency’ measured against the monetary quantity GDP [52]. Depletion of finite energy and other resources and environmental degradation is not seen as a significant barrier to economic growth, since there will always be more abundant substitutes (either natural resources or human-made capital).

In the 1990s, however, endogenous growth theorists have started to formally include concerns about environmental and resource factors limiting growth in standard growth models (e.g. [53,54]). Doing so, endogenous growth theory enables new insights about the relationships between resource scarcity, technical change, and economic growth, and hence constitutes a great leap forward compared with standard neo-classical growth theory. A further development of endogenous growth models to also account for rebound effects renders hope that in the future the relationship between economic growth, technical change and resource use (and eventually the size of various rebound effects on the macroeconomic level) can be better modelled and understood.

There are diminishing returns to the ability of technology to reduce the amount of human-made and natural capital that is required to extract resources. Technical change can offset diminishing returns, either by a shift to more productive or less resource-dependent technologies, or by employing technologies that use new or more abundant resources. Resource scarcity or depletion often increases the use of human-made capital to extract a unit of natural resource, so that additional costs occur that have to be included. Microeconomic analysis typically ignores macroeconomic and global effects of substitution, thus under-estimating thermodynamic limits, complementarity, irreversibility, waste, and scale (impact of trade) [55]. Technical change may thus alleviate scarcity limits, but on the other hand can be crowded out by resource scarcity. Such technical change enables greater rates of extraction than at the previous, lower level of efficiency in obtaining the mineral or fuel resources.

3. Insights concerning rebound studies and research needs

The following 12 observations are claimed to be insights that can guide further research into the empirical analysis of rebound effects. Not all of them follow directly from the foregoing, and for reasons of space we explain them only briefly.

1. Evaluations of government energy efficiency programmes are flawed because they usually take *only engineering quantities* into account, i.e. they implicitly and untenably assume that rebound equals zero, and *lack a global perspective*. The chapter on energy efficiency policies in a recent UK report, for instance, does not mention the rebound effect at all [56]. This practice should be abandoned forthwith and efforts redoubled to provide more evidence about the size of indirect rebound, and to settle the question of backfire. Another recent UK study has made significant strides toward this goal [27].
2. The models of energy consumption in such assessment studies should also avoid treating GDP and population as fully exogenous, because this begs the question of whether (and to what extent) energy efficiency contributes to economic and population growth. It should also be kept in mind that energy consumption may rise as well due to other kinds of growth-enhancing efficiency gains (organisational, institutional), but this should not be booked under energy rebound (lack of a technical change component).
3. Two concepts are crucial for rebound studies: that of engineering energy savings, of which rebound is a percentage, and that of the purchasing power increase (income effect), which must result from efficiency increases. How efficiency affects the price of energy is, on the other hand, more difficult to determine. Perhaps price remains constant while at the new equilibrium demand is greater [57]. Ultimately, what consumers want are energy services, not energy *per se*, the costs of which may be reduced by energy efficiency improvements.
4. The common concept in the rebound literature of ‘energy services’ should be reconsidered, because *every* good and service requires energy inputs—just as, perhaps, they require capital, labour and non-energy material inputs as in an ordinary production function $Q = f(K,L,E,M)$. The concept furthermore can lead to the conflation of physical and utility criteria.
5. Tractable though it may be, measuring *direct rebound* compared with engineering savings calculations is insufficient as a basis for policy advice. The ultimate goal must be the measurement of *total rebound*, i.e. direct and indirect rebound—demand for goods or services other than the newly more efficiently supplied one, demand by additional consumers who enter the market at the new, lower prices, and demand for totally new products or services which (at least partly) result from energy efficiency increases.
6. Any rebound analysis must apply both to business-as-usual or ‘autonomous’ energy efficiency increases [58] as well as policy-induced ones.
7. For statistical analysis, some physical metric or metrics enabling a rigorous definition and measurement of macro-level energy efficiency change (e.g. at the national or global level) must be found.
8. Energy efficiency increase *enables* (but does not always implicate) greater energy consumption; hence our analyses must include ‘the consumer’. That is, *saturation* or any deliberate decision to abstain from additional consumption (sufficiency strategy) does lower rebound, rendering large rebound effects, and the more so backfire, by no means an unavoidable consequence.
9. Further concerning ‘the consumer’, increases in energy efficiency are no panacea for either energy conservation or economic growth and welfare; demand saturation and substitutability of input factors matter a great deal, and both of them change over time, as do our needs and wants. An interesting topic in this respect is *status signalling*, i.e. situations where an individual communicates (honest or bogus) information about his/her status to other individuals that the others do not have [59,60]. Often it is the (perceived) relative consumption levels among consumers that determine needs and wants, and that impact the (perceived) status of an individual. As an example, someone may own a bigger car or house than the neighbours in order to signal to others a higher

economic or social status. Unfortunately, many status goods today are resource-intensive, making saturation or even a decline in total material or energy consumption less likely.

10. Perhaps we can learn from the history of increased *labour* efficiency. A consensus reigns that 'labour-saving' innovations did not save labour at all, but enabled, indeed, ever-increasing population and employment. If we discover the mechanisms responsible for this, can they shed light on the economic processes following *energy* efficiency increases [61–63]? Moreover, greater *time* efficiency in production, even holding the amount of useful work gained per unit of energy input, can free time for further production and consumption [13].
11. For policies to save energy resources it is important to determine, and to take into account, the approximate magnitude of total rebound. As rebound increases, energy efficiency policy becomes ever more ineffective as well as cost-ineffective, reaching counter-productivity beyond a level of 100%. The difficult debate over the paradoxical backfire issue, while of great theoretical interest, is thus not strictly pertinent to judging the effects of political measures mandating or encouraging greater efficiency.
12. Future research should begin with a broader and more accurate concept of efficiency itself. Efficiency is *both* less input for the same output or more output for the same input. While the latter case seems to well describe human history, where natural resources freed from one task are committed either to other tasks or to population growth, the former obtains only if people choose leisure and reproduce at no more than replacement rates. Embracing both types of efficiency change means studying economics as well as engineering, and raises the likelihood of policy-relevant new insights that actually help to curb energy consumption.

Not only is there at present no viable methodology for measuring indirect or economy-wide rebound, but these two concepts are themselves poorly defined. Microeconomic tools can describe the elasticities to be discovered, but data at aggregate levels to estimate such elasticities are lacking. We know that technological efficiency increases expand the production possibilities frontier—we are enabled to consume both more end product and more inputs, whether of energy, materials or labour. We know that over the last 200 or more years energy consumption has risen and real energy prices have fallen; and it is safe to assume that technological efficiency has also risen. But whether this correlation reflects causality is undetermined. In deciding whether to prescribe or subsidise energy efficiency improvements beyond those that take place as business-as-usual, it is of crucial importance to know the size of the economy-wide (global) rebound. Otherwise, energy efficiency policies become ineffective, or even counterproductive, as rebound rises, with important implications for policy design and the achievability of, say, energy supply security or greenhouse gas mitigation targets.

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