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# From Unidisciplinary to Multidisciplinary Rebound Research: Lessons Learned for Comprehensive Climate and Energy Policies

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This article presents how the rebound phenomenon has evolved from only being considered from a neoclassical economic perspective to include several other disciplines such as psychology, sociology, and industrial ecology. The intention is to show how different theoretical perspectives contribute to the scientific discourse about rebound effects. We summarize key findings from the various disciplinary strains of research and highlight new research questions and needs that arise. We discuss strengths and limitations of the expansion toward multidisciplinary rebound research and suggest that a further expansion toward transdisciplinary research could be valuable. We identify the "micro-macro discrepancy" and the "cause-effect relativity" as two general challenges that have to be taken into account when rebound research becomes increasingly multi- and transdisciplinary. In the final section of the article, we present lessons learned from multidisciplinary rebound research for policies and measures that aim to mitigate rebound effects. The main finding of this article is that if policymakers aim to make climate and energy policies as "rebound-proof" as possible, findings from both energy economics and multidisciplinary rebound research have to be taken into account.

**Keywords: sustainable production and consumption, energy economics, energy efficiency, climate policy, rebound proof policy, green growth, post growth, degrowth**

## INTRODUCTION

The recently presented IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, stress that we "require rapid and far-reaching transitions in energy, land, urban and infrastructure"; which – still according to this report – will imply "systems transitions … unprecedented in terms of scale … and imply deep emissions reductions in all sectors" (IPCC, 2018a: 2). The special report points out that changes in lifestyles – together with fossil-fuel-based material consumption – are major drivers of global resource use and are together the main contributors to rising greenhouse gas (GHG) emissions (IPCC, 2018b: 61). Current climate change mitigation policies and Nationally Determined Contributions (NDCs) under the Paris Agreement are not consistent with a 1.5°C warmer climate (IPCC, 2018a,b).

Furthermore, relying on carbon capture and storage (CCS)—also termed "negative emission" technologies—to fill this gap does not appear to be a viable insurance policy, "but rather an unjust and high-stakes gamble" (Anderson and Peters, 2016, p. 183). This leaves society in a situation to growing urgency to implement mitigation measures with the potential of high GHG emission reduction.

Improving the energy efficiency of certain applications, sectors, and entire economies is considered a major contribution to reach climate and energy policy goals (IPCC, 2014). Numerous studies document the potential of energy-efficiency improvements to mitigate climate change (Worrell et al., 2009; Duan et al., 2017; IEA, 2017). Yet rebound research places a question mark on the assumption that energy-efficiency improvements and lifestyle changes can deliver quick and drastic reductions in GHG emissions. It departs from the evidence that the final effect of the many efforts launched throughout past decades, with an honest promise of delivering major increases in energy efficiency has all too often been proven to be partly or fully neutralized by newly increased energy demands (Sorrell, 2015). This is also observed for the case of promoting energy-efficiency motivated lifestyle changes (Bjelle et al., 2018). Data worldwide have shown signs of decline in energy use per unit of consumption (IEA, 2014; IPCC, 2014; Santarius et al., 2016). However, improvements in energy efficiency have not been enough to bring about an overall reduction in energy use globally. For instance, in 2016 global energy intensity decreased by 1.8%, but at the same time, global energy demand increased by 1.1% (IEA, 2017). The fact that energy demand increases in most countries despite energy-efficiency improvements is even more sobering when shifting from using territorial statistics, based on energy use within a country, toward accounting for energy use associated with a country's consumption (Bruckner et al., 2012; Peters et al., 2012; Santarius et al., 2016; Bjelle et al., 2018).

One explanation for this paradox, that improvement in energy efficiency has not be able to yield a decline in the absolute energy use, can be found in the systemic relationship between efficiency and expansion, or notably, the rebound effect (Santarius et al., 2016). Although energy efficiency is promoted strongly by several countries and the EU, for instance, by their 2030 energy-efficiency guidelines, the rebound effect phenomenon questions whether energy efficiency will lead to substantial reductions in GHG emissions. To find policies that meet the Paris Agreement goal of limiting climate change at 1.5°C warming, it is crucial to find policies that could contain possible rebound effects (Santarius et al., 2016).

The assumption of this article is that the complex mechanisms underlying the phenomenon of the rebound effect are yet to be fully understood; and as time appears to be running out for achieving the 1.5°C, and even the 2.0°C goal, it becomes increasingly important to ensure that GHG mitigation efforts are 100% effective—with no rebound effects. Manifold studies on rebound effects have been published, and several meta-analyses and reviews have been conducted (e.g., Greening et al., 2000; Sorrell et al., 2009; Jenkins et al., 2011; Maxwell et al., 2011; Azevedo et al., 2012), but we share the impression given by Turner's review, "*…that empirical rebound research has run ahead of the required theoretical and analytical underpinnings*" (Turner, 2013, p. 25). Our hypothesis is that expanding the research on rebound effects from energy economics into other scientific disciplines improves theoretical understanding of the rebound phenomenon, offers new methodologies to empirically investigate the scope of rebound effects, and generates new insights for policymakers on how to design climate and energy policies that better allow for the containment of such effects.

This paper builds on a book about the rebound phenomena carried out by the authors of this article (Santarius et al., 2016). We present the most important insights gained from the book while adding new research and perspectives. Section Terminology and Scope, Size, and Explanations of Rebound Effect address the terminology and scope of rebound effects. Section Multi-Disciplinary Rebound Approaches Beyond Economics then looks at how explanations for rebound phenomena have developed from being dominated by neo-classical economics to include other perspectives—and also other disciplines within the social sciences, such as psychology, urban planning, and sociology, as well as from natural sciences, including thermodynamics and industrial ecology. Broadening rebound research by several disciplines will foster sounder theoretical explanations. On the contrary, it runs the danger of leading to a blurring of the concept and what is meant with rebound effects. To address this challenge, we suggest two key principles in section Lessons Learned for Rebound Research. Finally, section Lessons Learned for Rebound Policies draws on a conclusion from the various disciplinary approaches for policies and measures to mitigate rebound effects.

## TERMINOLOGY AND SCOPE, SIZE, AND EXPLANATIONS OF REBOUND EFFECT

IPCC (2014 p. 28) states "There is general agreement that rebound effects exist, whereby higher efficiency can lead to lower energy prices and greater consumption, but there is low agreement in the literature on the magnitude." Three different positions can be found in this debate (Santarius et al., 2016, p. 8):

> Rebound effects are limited due to demand saturation and negligible energy cost and therefore are of minor importance (e.g., Lovins, 1988; Schipper and Grubb, 2000).
>
> Rebound effects are of at least some importance, but they need not result in energy efficiency polices becoming substantially ineffective (e.g., Sorrell, 2007; Gillingham et al., 2013).
>
> Rebound effects are significant, and improving the efficiency of energy use might not lead to reduced energy use nor be an effective policy for reducing GHG emissions (Saunders, 1992, 2000, 2013; Ayres and War, 2009).
>
> The point of departure for our book (Santarius et al., 2016) and this article is the need to shift from merely a focus on quantifying rebound effects toward understanding why and how rebound effects occur (Turner, 2013; Walnum et al., 2014; Santarius, 2015a,b; Santarius et al., 2016).

The dominating research approach on rebound mechanisms during the past 35 years has been that of energy economics, which explains the occurrence of rebound effects by referring to both income and substitution effects. Within the energy economist's tradition, three categories of rebound effects are usually found: direct, indirect, and economy-wide rebound effects (Sorrell, 2007). We draw on these categories, yet suggest another taxonomy that highlights the different levels of action at which rebound effects are generated. This better allows for analysis of the actual mechanisms and causes that lead to those effects. The largest part of the existing rebound literature focuses on effects at the consumer side (households, end-use consumers). We define these effects as "microeconomic rebound effects." Yet rebounds can also occur in the process of production, which stems back to William Stanley Jevons' analysis from 1865. We suggest defining all producer-side and market-level effects as "mesoeconomic rebound effects" (see also Santarius, 2015b). Finally, several studies have investigated, at the aggregate level, the extent to which energy-efficiency improvements lead to overall economic growth and how this rebounds on overall energy demand. We suggest defining these effects as "macroeconomic rebound effects." All effects together sum up to the "economy-wide rebound effect" (Jenkins et al., 2011; Santarius et al., 2016). We will now briefly mention key theoretical and empirical findings from the past decades of rebound literature and assign them to the categories of micro-, meso-, and macro-economic rebound effects.

Several meta-analyses have looked at the direct rebound effect (Greening et al., 2000; Sorrell, 2007; Jenkins et al., 2011; Madlener and Alcott, 2011; Maxwell et al., 2011; Azevedo et al., 2012). Usually, direct rebound effects are found to be on the order of 10–30% (Sorrell et al., 2009; Santarius et al., 2016). However, looking more closely into the debate connected to the direct rebound effect, the size of the direct rebound effects varies considerably in different sectors and between countries. One reason for this difference is how energy efficiency is defined and how elasticity is calculated.

Indirect rebound effects have only been partly researched so far (see, e.g., Druckman et al., 2011; Azevedo and Thomas, 2013; Chitnis et al., 2013, 2014; Lin and Liu, 2015). The rather conservative assumption that additional real income will be spent equally according to the average consumer basket suggests that indirect rebound effects should be at least on the order of 5–10% (Santarius, 2015c). However, Chitnis et al. (2014) find that the size of indirect rebounds greatly depends on the sector in which energy-efficiency improvements take place: "First, rebound effects appear to be fairly modest (0–32%) for measures affecting domestic energy use, larger (25–65%) for measures affecting vehicle fuel use and very large (66–106%) for measures that reduce food waste" (p. 21). More research is needed to both theoretically explain and empirically examine indirect microeconomic rebound effects.

An under-researched area of rebound analysis has been that of production-side rebounds or "mesoeconomic rebound effects," that is, to study how firms, sectors, and markets react to energy-efficiency improvements (Santarius, 2015b). This concept was first addressed by Greening et al. (2000), who pointed to two particular forms of rebound effects by firms: "output effects" and "factor substitution."

However, they did not conduct an empirical or theoretical study to uncover their size (see also Sorrell, 2007; Sorrell et al., 2009; Jenkins et al., 2011). Some theoretical contributions have been made by Michaels (2012), Borenstein (2013), and Turner (2013). They mention the same relationships that happen in the case of macroeconomic effects, namely, that the interface of labor, capital, and energy as factors of production changes throughout the economy can lead to overall economic growth (Santarius, 2012). In addition, a limited number of empirical studies investigate mesoeconomic rebounds within industry sectors (Bentzen, 2004; Safarzynska, 2012; Saunders, 2013; Lin and Li, 2014). Bentzen calculates an average rebound effect on the order of 24% for the entire producing industry in the USA. Lin and Li (2014) find rebounds in the order of 74% for heavy industries in China. Saunders (2013) disaggregates 30 sectors of US industry and calculates average rebound effects between 30 and 60% for most sectors, while some sectors (e.g., electricity generation) show evidence of "backfire." These few econometric studies underpin an extrapolation made earlier by Birol and Keppler, who suggested that "The rebound effect … increases with the level of aggregation. We would expect the rebound effect at the level of the single firm or the single consumer to be smaller than at the level of the sector, and the rebound effect at the sectoral level to be smaller than the rebound effect at the national level." (Birol and Keppler, 2000, p. 463). While certainly much more empirical, econometric, and theoretical work is needed to investigate mesoeconomic rebound effects. This conclusion is underpinned by a handful of studies available for the sector of freight and air transportation (Gately, 1990; Graham and Glaister, 2002; Anson and Turner, 2009; Matos and Silva, 2011; De Borgera and Mulalic, 2012). These studies find direct rebound effects between 17 and 80% in freight transportation, which lies above the average of about 10–30% direct rebounds in personal automotive transportation (Sorrell et al., 2009).

At the macrolevel, we see debate about how energy as a factor of production leverages overall economic growth, the degree of substitutability of all factors of production, and the relationship between efficiency increases and product/service innovation (Sorrell, 2007; Madlener and Alcott, 2009; Turner, 2013), showing how the dynamics between energy efficiency and overall economic growth work on the basis of macroeconomic growth models is a challenging task. However, the results of the models depend on underlying assumptions (Walnum et al., 2014; Santarius, 2015c). Hence, results of econometric analysis vary not only due to the country under consideration, but also due to the methodology applied. At the lowest end of all studies, Barker et al. (2007) find an effect on the order of 24% for Great Britain, while Turner et al. (2009) find a backfire effect of approximately 90% for the same territory. To better understand the linkage between energy efficiency and output growth, it might be useful to look at causes outside the energy economic realm and from other disciplinary perspectives (Santarius et al., 2016). As we will show in the next section, research on macroeconomic (or "macrolevel") rebound effects from other disciplines has only just begun.

## MULTIDISCIPLINARY REBOUND APPROACHES BEYOND ECONOMICS

While the study of rebound effects traditionally pertained to the domain of neoclassical energy economics, the concept in recent years has been broadened to other disciplines. This implies that structures (physical infrastructures, economic and political systems, mental mechanisms) as well as other variables (e.g., habits, lifestyles, change of attitudes and norms) that go beyond "saved money" should be considered for an understanding of the causes of rebound effects (Walnum et al., 2014). We argue that the use of multidisciplinary approaches increases the understanding of the overall rebound phenomenon. In particular, it identifies additional causes and mechanisms that trigger such effects, while also providing new grounds for empirical analyses (Santarius, 2015a).

### Psychology

"Psychological" or "motivational rebound effects" rest on the assumption that energy-efficiency improvements not only have a price content, as Khazzoum pointed out in his ground-breaking rebound publication (Khazzoom, 1980), but may also have a symbolic and social content (Santarius, 2015a). According to Santarius and Soland, psychological rebound effects can be defined "as an increase in energy service demand due to a change in consumer preferences that can be attributed to an increase in technological energy efficiency" (Santarius and Soland, 2018, p. 415). Research on psychological rebound can still be counted on two hands. On the basis of Thaler's mental accounting framework, Girod and de Haan (2009) analyzed psychological rebound effects. Paech (2011), as well as Santarius (2012), introduced social and behavioral science perspectives in a rather essayistic style. Otto et al. (2014) suggested psychological rebounds and mainly criticized neoclassical assumptions of homo oeconomicus' profit-maximizing intentions. Other researchers (Peters et al., 2012a; Peters and Dütschke, 2016; Santarius and Soland, 2018), presented theoretical approaches to psychological rebounds, that were mainly built on the theory of planned behavior (TPB) and the norm activation model (NAM). Santarius and Soland (2018), developed a taxonomy of different motivational rebound effects and presented an integrative theoretical framework on how these interlink with microeconomic rebound effects. As for empirical research, Peters et al. (2012b) researched the issue with qualitative methods, i.e., focus groups in Germany. Suffolk and Poortinga (2016) investigated behavioral changes after the introduction of energy-efficiency improvements in housing. They presented the first attempt to investigate psychological rebounds with quantitative empirical methods; yet their study does not deliver robust results. Hence, more research is needed on psychological rebound effects.

### Sociology

Investigating the rebound effect through a sociological lens has just yet began. For microlevel effects generated by individuals, Galvin and Gubernat deployed a practice theoretical framework, first introduced by Theodore Schatzki, to examine the interrelationship between "human-material arrangements." Adding a quantitative thought experiment, they showed that the quantitative scope of rebounds is much larger when comparing this approach to traditional microeconomic approaches. For macrolevel rebound effects, Santarius (2016) deployed a time-theoretical framework by Rosa (among others) to examine whether the speed of life and the phenomenon of social acceleration can be partly attributed to technical (energy)-efficiency improvements. Santarius linked his theoretical considerations back to economics and suggested that investigations on the relationship between energy efficiency and the speed of capital turnover may add to an improved theoretical understanding of macroeconomic rebound effects.

### Industrial Ecology

The perspective of industrial ecology suggests broadening the concept of rebound to include lifecycle environmental consequences of overall demand changes as a result of technical efficiency improvements in products, in liberating or bounding consumption, and in production. Efficiency changes are understood more broadly as "environmental efficiency," since resources (including energy carriers), emissions, and waste generation can be integrated into the theoretical frameworks deployed (Goedkoop et al., 1999; Hertwich, 2005; Spielmann et al., 2008; Murray, 2013; Vivanco, 2016). Whereas results following the classical energy rebound effect are often in the range of 10–30% for direct microeconomic rebound effects (see section Terminology and Scope, Size, and Explanations of rebound effect), those following the "environmental rebound effect" typically assume a wide range of values (including values far above 100% and below-100% (Vivanco, 2016). The strengths of the industrial ecology perspective is that tradeoffs between indicators can be easily identified, and innovations that do not exclusively target energy reductions can be studied as well. For example, electric cars may bring about energy-efficiency improvements in mileage, but may also aim to reduce carbon emissions and local air pollutants, such as particulate matter and NOx, as well as noise (Vivanco, 2016).

### Evolutionary Perspective

A contribution to the rebound discourse has come from theories associated with physics. Giampietro and Mayumi (2008) suggested that the rebound effect reflects the natural tension between two contrasting principles: the minimum entropy production and the maximum energy flux. Living systems make changes in functions and structures over time (Giampietro and Mayumi, 2008; Walnum et al., 2014). An increase in efficiency (by doing things better) makes it possible to assign a larger fraction of the accessible resources to adaptability (learning how to do things differently). Rebound research from an evolutionary perspective also depicts a tradeoff between efficiency and power; for example, cars could become more efficient, but this could be outstripped by making them more powerful over time (Ruzzenenti and Basosi, 2008a,b; Walnum et al., 2014). Network theory added complexity by including more nodes such as improvements in the freight transport system, which could lead to unexpected structures at the global level (Ruzzenenti et al., 2015; Ruzzenenti and Basosi, 2017). Connecting this theory to complex systems and network theory showed that efficiency measured on a per unit base would not lead to straightforward saving, since added complexity and changes in structures can cause more use of energy (e.g., outsourcing and globalization in commercial freight transport) (Ruzzenenti and Basosi, 2008a).

## Transdisciplinary Perspectives With a View To Real-World Conditions

In addition to these disciplinary approaches, there is an increasing share of literature that investigates rebounds in actual policy cases and under real-world conditions. The edited volume by Santarius et al. (2016) emphasized that much of today's economic rebound literature can only, to a limited extent, explain the emergence and appearance of rebound effects due to limitations of the applied categories and definitions and blind spots of methodological approaches. Yet the same may be true for other disciplinary approaches, each of them providing only a specific lens on the real-world's complexity. We do believe that any disciplinary approaches, such as analyzing rebounds on grounds of price elasticities (rebound economics), changes in motivation (rebound psychology), structural changes (rebound sociology), lifecycle analysis (industrial ecology), systems and network theory (evolutionary perspectives), and so on, each provide their own distinctive insights. But applying the rebound concept to urban planning, tourism, the labor market, ICT services, or other respective sectors and case studies, show that pure "laboratory-like" effects of efficiency elasticities, attitudinal changes, and the like can hardly be isolated when considering the praxis.

Hence, an important insight from our book (Santarius et al., 2016) was that rebound effects could not be seen in isolation from its real-world contextualizations and that effective policy making should take into account other causes and effects that could impact the implementation of energy and climate policy. We concluded that to better grasp these interrelationships, rebound researchers should broaden their research designs even beyond interdisciplinary approaches and toward transdisciplinary research (Pohl and Hadorn, 2008; Lang et al., 2012). This involves empirical research in collaboration with societal actors (e.g., companies, the State) and requires research designs that aim to be as close to the praxis as possible. While such transdisciplinary approaches may generate more robust outcomes, they may run the danger of coming at the price of scientific accuracy, which we will now address in the next section.

# DISCUSSION

## Lessons Learned for Rebound Research

When summing up the lessons learned from rebound research and the potential policy relevance from this, we can differentiate between the levels of society in which rebound effects occur and could be addressed, and actions to be taken to mitigate such effects (cf. **Table 1**).

**TABLE 1 |** Lessons learned for rebound research.

| Levels of society | Action to be taken |
|---|---|
| Theoretical understanding | Address the micro-macro discrepancy<br>Address the cause-effect relativity |
| Policy strategy | Move from effect to cause-oriented policies<br>Integrate climate and energy policies and set energy-demand goals |
| Policy means | Include all emission sources and countries in global emission cap and trading systems<br>Implement emission cap and trade systems within a policy mix<br>Design ecotaxes that are smart and flexible<br>Dynamize efficiency standards and embed them into a broader policy mix<br>Address psychological rebound effects through sustainability communication |

### Micro-Macro Discrepancy

Given the evolving and broadening rebound discourse, two general challenges of all rebound research become increasingly evident: the micro-macro discrepancy and the cause-effect relativity (Santarius, 2015d). The micro-macro discrepancy results from the inevitable gap between the limits of any particular rebound analysis and the possible effects beyond those limits. For example, more energy-efficient cars can enable their owners to drive more miles (direct rebound effects). But only looking at direct effects hides the fact that such efficiency improvements can also set in motion various indirect effects in the rest of the transport sector, in other sectors beyond transport, or, as Alcott (2005) pointed out, even beyond the borders of a country. The smaller the scope of any particular rebound analysis compared to "the world," the less reliable are the concrete numbers on the extent of the rebound effects derived from that analysis. Hence, the narrower a research approach is defined, e.g., unidisciplinary and focusing on microlevel effects only, the more carefully the results should be treated in light of the challenges of the micro-macro discrepancy.

At the same time, there is some danger to equalize the rebound effect with any kind of growth effect. Nor is it helpful to speak of the "gross rebound effect," as Holm and Englund did in 2009. Despite the fruitful interdisciplinary extension of rebound research, the concept of rebound should be confined to the specific role that efficiency and productivity play for increased demand. However, will efficiency always serve as a strictly necessary and sufficient cause?

### Cause-Effect Relativity

Rebound analysis has to cope with the cause-effect relativity, which means that it has to face the challenge of isolating the specific role of efficiency from other influencing factors in real-world situations that do not conform to laboratory conditions. Even (micro-)economic rebound explanations (i.e., income and substitution effects) cannot claim a strong causal relationship: Multiple parameters usually shape an individual's decision on how to spend money saved through, say, a car's increased fuel efficiency. Restricting the cause of rebound to price effects is not any more authoritative than explaining increased consumption through, for example, motivational changes (see Santarius and Soland, 2018). Hence, the broader the approach used in researching rebound effects, such as inter- and transdisciplinary approaches instead of disciplinary approaches, the more specific the definition of the effects investigated and the methodologies applied should be in light of the challenges of the cause-effect relativity.

Yet neither the micro-macro discrepancy nor the cause-effect relativity should be used as a thought-terminating argument for rebound research on the whole. Newton mechanics is still considered highly valuable by many scientists, although it has been put into perspective by Einstein's theory of relativity. Most causalities described by social science theories will not satisfy the claim for strictly necessary and sufficient causes. Rebound research should: (1) Clearly (and most narrowly) define the kind of rebound effect under investigation, and (2) Make transparent how both the cause-effect relativity and the micro-macro-discrepancy is taken into account. This entails that rebound research always needs to (1) Plausibly argue why (energy) efficiency is considered a primary cause of the effect under investigation, and (2) Make transparent the assumptions as well as the boundaries of the investigation at hand.

## Lessons Learned for Rebound Policies

### Move From Effect to Cause-Oriented Policies

The Brundtland report presents two alternative environmental policy strategies: The effect- and the cause-oriented strategy (WCED, 1987). The effect-oriented strategy puts weight on mitigating the negative effects to the environment from human activity; whereas, the cause-oriented strategy puts weight on addressing the drivers behind the unacceptable negative environmental effects that occur. The report states that effect-oriented strategy prevailed. This situation has continued after 1987 (Høyer, 2010). The Brundtland report called for a shift from an effect-oriented toward a cause-oriented environmental policy strategy. Still, more than 30 years after the presentation of the Brundtland report, it is sad to note that this has not happened.

Our edited volume (Santarius et al., 2016) on the rebound effect and climate change supports the message from the Brundtland report; i.e., going for the cause-effected strategy gives a better chance of achieving the Paris agreement. Examples of an effect-oriented strategy in the case of climate change are adapting to climate change and capturing and storing carbon; whereas, addressing the drivers of GHG emissions and understanding—and addressing—rebound effects involved in policy measures to reduce GHG emissions are examples of a cause-oriented strategy. As for the case of environmental policy in general, climate policy is still dominated by the effect-oriented strategy. Gaining a better understanding of rebound mechanisms involved in climate policy implementation is an important part of reinforcing the cause-oriented strategy.

### Integrate Climate and Energy Policies and Set Energy-Demand Goals

The overall policy problem that rebound analysis exposes is twofold: Firstly, few policy strategies include policy measures on reducing the level of energy consumption. Secondly, few policy strategies entail full integration of climate and energy policies. The really "big assumptions" that have not been comprehensively questioned in either the climate or the energy policy debate are (1) that it would be possible to fully substitute fossil-fuel energy use by GHG-free energy sources, (2) that this could be done in time to achieve the 2.0—not to say the 1.5—degree climate policy goal, and (3) that, at the same time, global energy consumption could continue to grow. These assumptions are extremely problematic for at least two reasons: Firstly, the energy intensity measured in any way (per ton, square meter, etc.) is dramatically lower for any renewable source of energy compared to that of fossil energy—but it is never zero! And secondly, society will have to adapt to climate change even if global GHG emissions immediately ceased, and adaptation measures will, in many cases, require an increase in energy use. As stated in our edited volume, we therefore come to the conclusion that "a post-carbon and climate change-resilient society must most probably also be a low-energy society" (Santarius et al., 2016, p. 288).

### Be Aware That Even Global Emission or Energy Limits Are Not the Silver Bullet Against Rebound Effects

Literature abounds, which suggest a global emission cap-and-trade system are a good policy instrument for reducing rebound effects (e.g., IPCC, 2014). Yet, in practice, global caps will not serve as a silver bullet against the rebound phenomenon. Firstly, it appears that an effective global emission is not yet likely to be included in current multilateral climate policy agreements and, in particular, if such a policy measure would cover all energy as well as land-use-related emissions taking place in all categories of countries, be they rich or poor, "north" or "south." As long as some emission sources, or some countries, are not part of the cap, leakage could occur (on leakage, see below).

Second, the evolution from unidisciplinary, economic rebound research to multidisciplinary rebound approaches suggests that it is not appropriate to assume that rebound effects disappear if a global cap is installed. For instance, psychological rebound effects could still occur: Moral licensing or value changes could motivate consumers to substitute less energy-intensive products or services with more energy-intensive ones (Santarius and Soland, 2018). Likewise, sociological rebound effects could still occur: For example, if increased energy efficiency alters urban patterns or accelerates the speed of life, this may generate structural rebound effects (Santarius, 2016). While psychological or sociological rebounds would not necessarily inflate the cap, their occurrence would increase the ambition of policymakers to ensure compliance and stringently tighten the cap over time until far-reaching climate policy goals are achieved (i.e., zero emissions in industrialized countries by the second half of the Twenty-First century). The continued occurrence of rebound effects poses a constant threat to the implementation of and the compliance with emissions caps (and other policy measures) if the causes of those effects are not addressed. If the societal mechanism is allowed to continue, in which efficiency and expansion trigger an accompanying increase in demand and economic output, then society will keep on struggling to achieve the scale of global GHG emission cuts outlined in the Paris agreement. Thus, as stated in our edited volume (Santarius et al., 2016), it is urgent to redesign current climate and energy policy strategies to make them as "rebound proof" as possible.

### Consider Leakage and Moral Licensing From Nonglobal Cap-and-Trade Systems

If caps only apply to individual countries or regions (such as the EU), the displacement of emissions to other countries can reduce the effectiveness of these caps (leakage). Yet even within a country, it will hardly be possible to set national caps for all emissions sources. For example, the EU's emissions trading system (EU ETS) merely caps emissions-intensive installations, so that it (only) covers around 50% of EU emissions. Even if the EU was a "closed economy" from which leakage to other countries could not take place, indirect rebound effects could still occur if the demand from sources and sectors covered by the EU ETS were transferred to other sources and sectors outside the EU ETS. Moreover, and again, caps would not prevent psychological or sociological rebound effects. If a cap would effectively restrict emissions from one sector, say car travel/ ground transportation, consumers might feel morally licensed to use airplanes even more. As the overall lessons learned, therefore, even cap-and-trade systems should be implemented within a policy mix.

### Design Ecotaxes Smart and Flexible

Weizsäcker et al. (2009), among other researchers, proposed an ecological tax reform in which tax rates on energy carriers (electricity, fuel, etc.) rise in line with efficiency improvements. This way, cost savings achieved through efficiency can be "siphoned off" by taxes and incentives to keep improving efficiency are maintained. Despite being a very valuable proposal, the attempt to contain rebound effects through ecotaxes encounters at least three challenges.

Firstly, ecotaxes can only curb income and market-price effects; psychological, sociological, and, to some extent, macroeconomic rebound effects (i.e., efficiency-induced economic growth effects) are not necessarily contained by cost increases. It is therefore unclear to what extent the total sum of all rebound effects can be curbed by ecotaxes.

Secondly, the implementation of ecological tax, which is specifically designed to counter rebound effects, could face significant political and social problems. There is bound to be a tradeoff between the effect of setting a price on efficiency gains and the social costs of the tax. As Saunders (1992, 2000) has shown, the more inelastic the substitution elasticity between the natural resource factor and other factors (labor, capital), the higher the tax rates must be to actually affect demand. With regard to rebound effects, the reverse holds true: the more elastic the substitution capacity, the more readily a low tax rate will bring about a change in behavior or investment. Unfortunately, extensive rebound effects are then likely to occur. In short, high elasticity leads to high rebounds at low cost as a result of ecotaxes, while low elasticity leads to low rebounds at high costs. When considering the introduction of ecotaxes specifically intended to contain rebound effects, it should therefore be borne in mind that they may encounter social acceptance problems, possibly far in excess of the political acceptance problems that previous energy/fuel taxes and ecological tax reforms have faced (see also Beuermann and Santarius, 2006).

Thirdly, therefore, if the different substitution elasticities of different sectors and product groups are taken into account, ecotax rates would have to be rigorously differentiated according to sectors and products. A general ecotax rate based on the aggregated (national) efficiency improvement cannot ensure that rebound effects are adequately contained. However, experiences of the challenging political processes of introducing previous ecotax systems in several countries indicate that a complex ecotax design with numerous different sector- and product-specific tax rates is unlikely to be feasible in real-world politics.

### Dynamize Efficiency Standards and Embed Them Into Broader Policy Mix

Of all efficiency-boosting policies, command-and-control measures such as mandated efficiency standards for products or production processes run the highest risk of triggering rebound effects. In particular, "win-win" opportunities—in which the additional costs of an efficiency improvement are quickly recouped—are particularly likely to generate rebound effects (see also Sorrell, 2007). Suggestions by the IPCC (2014) and the IEA (2014) that substantial savings of greenhouse gas emissions can be achieved at zero or even negative cost will not achieve the envisaged results, because the scenarios on which they are based take no account of rebound effects. Three lessons learned can be drawn. (1) Wherever possible, efficiency standards should be "dynamized," i.e., should increase over time, such as in the case of the top runner model (Jänicke, 2012). (2) Efficiency standards should be combined with market-based instruments (taxes, emission trading) so that rebound effects are partially contained. (3) When the introduction of a cost-neutral efficiency standard looms, policymakers might consider an assessment of the backfire risk. If efficiency standards are likely to trigger extensive rebound or even backfire, alternative measures should be considered.

### Address Psychological Rebound Effects Through Sustainability Communication

The fact that there are many different reasons for rebounds and for the mechanisms behind the various effects suggests that efforts to reduce them should not focus solely on command-and-control and market-based instruments, but should be extended to include sustainability communication measures of all types that aim to influence the knowledge and values of consumers and producers (see Santarius, 2012). Such measures include environmental education, sustainability advertising campaigns, and ecolabel schemes as well as environmental management systems, environmental audits, and green marketing, to name but a few. In particular, psychological rebound effects, if it is possible to tackle them at all, can be addressed only through instruments of sustainability communication.

However, although much has been done to raise environmental awareness, efforts to change actual environmental behavior have so far met with little success. (Abrahamse et al., 2005) who conducted a meta-analysis of various empirical studies on energy behavior, concluded: "Information tends to result in higher knowledge levels, but not necessarily in behavioral changes or energy savings." (2005, p. 273) This conclusion is backed by Osbaldiston and Schott (2012), who conducted another meta-analysis of 253 studies. In addition, the quantitative extent to which sustainability communication measures can diminish rebound effects remains unclear. Hence, they should form part of the policy mix and be used with other instruments to educate people about the diverse causes of rebounds and the complex linkages involved. Nevertheless, it is worth exploring how sustainability communication measures could be refined for the specific purpose of addressing rebound effects.

## AUTHOR CONTRIBUTIONS

TS is the lead author for this article. He designed the article and wrote key parts of the article. HW contributed to the design of the article. He as well wrote key parts of the article. CA contributed significant parts to all sections of the article.

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