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The Jevons paradox unravelled: A multi-level typology of rebound effects and mechanisms

Steffen Lange [a,b,*], Florian Kern [a], Jan Peuckert [a], Tilman Santarius [a,c,d]

[a] Institute for Ecological Economy Research, Berlin, Germany
[b] Resource Economics Group, Humboldt-Universität zu Berlin, Berlin, Germany
[c] Technische Universität Berlin, Department of Social Transformation and Sustainable Digitalization, Berlin, Germany
[d] Einstein Centre Digital Futures, Berlin, Germany

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ABSTRACT

Literature on the rebound phenomenon has grown significantly over the last decade. However, the field is characterized by diverse and ambiguous definitions and by substantial discrepancies in empirical estimates and policy proposals. As a result, cumulative knowledge production is difficult. To address these issues, this article develops a novel typology. Based on a critical review of existing classifications, the typology introduces an important differentiation between the rebound *mechanisms*, which generate *changes* in energy consumption, and the rebound *effects*, which describe the *size* of such changes. Both rebound mechanisms and rebound effects can be analytically related to four economic levels – *micro*, *meso*, *macro* and *global* – and two time frames – *short run and long run*. The typology is populated with eighteen rebound mechanisms from the literature. This contribution is the first that transparently describes its criteria and methodology for developing a rebound typology and that gives clear definitions of all terms involved. The resulting rebound typology aims to establish common conceptual ground for future research on the rebound phenomenon and for developing rebound mitigation policies.

1. Introduction

Two conservative scenarios of the IPCC estimate total energy consumption must be reduced by approximately 15% globally by 2050, compared to 2010 [1]. According to the International Energy Agency [2], energy efficiency is “responsible for 60% of the [energy] savings” (p. 303). However, a large body of literature on the rebound phenomenon has emerged which questions whether this strategy suffices.

This literature includes several classification proposals but “there is still no agreed comprehensive taxonomy” [3]. Also, there has been little debate about the purpose of these typologies and their development. Turner [4] argues against developing classifications too early. We argue that, given the extent of research on the topic, it is time for a typology and that it should pursue two goals. First, it should serve as a heuristic model to understanding the determinants of the size of rebound effects. This requires integrating theoretical and empirical research. Second, the typology should facilitate the development of policy responses to the rebound phenomenon. We show that existing typologies can be improved in several respects to serve these goals.

Building on existing typologies, we systematically develop a multi-level typology along two dimensions: economic levels, i.e. micro, meso, macro and global levels, and time, i.e. the short and the long run. Moreover, we distinguish between rebound effects and rebound mechanisms. A rebound effect relates to the quantitative size of a (measurable) impact on energy consumption while a rebound mechanism is a qualitative relation, e.g., a cause-and-effect chain from an energy efficiency improvement to energy consumption. The term rebound phenomenon is used in the following when we refer to the issue of rebound in general – encompassing both rebound effects and mechanisms. We aim to establish more common ground regarding the conceptual relationships between rebound effects and rebound mechanisms on different levels and, thereby, to improve future empirical and theoretical research on rebound effects. Fig. 1 illustrates the relationship between rebound mechanisms and rebound effects and provides definitions for these two central terms.

The remainder of the paper is structured as follows: Section 2 briefly reviews the relevant literature on the rebound phenomenon, indicating

Abbreviations: CGE, Computable General Equilibrium; ESCI, Emerging Sources Citation Index; IPCC, Intergovernmental panel on climate change; SCI-Expanded, Science Citation Index Expanded; SSCI, Social Science Citation Index; R, Rebound effect; AS, Actual savings; PS, Potential savings.

* Corresponding author at: Institute for Ecological Economy Research, Potsdamer Str. 105, 10785, Berlin, Germany.
E-mail addresses: steffen.lange@ioew.de (S. Lange), florian.kern@ioew.de (F. Kern), jan.peuckert@ioew.de (J. Peuckert), santarius@tu-berlin.de (T. Santarius).

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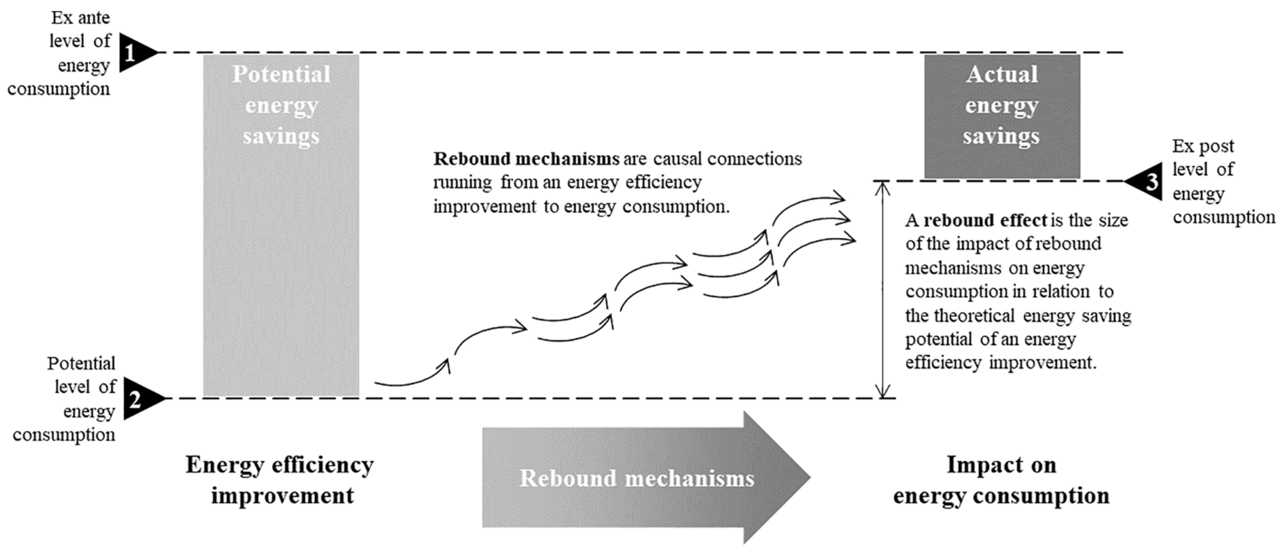

Fig. 1. The relationship between energy efficiency improvements, rebound mechanisms and rebound effects. This figure presents the definitions and illustrates the conceptual distinction between rebound mechanisms and rebound effects. The size of the rebound effect is defined by the relationship between three levels of energy consumption: 1) "ex ante", i.e. before the efficiency improvement, 2) "potential", i.e. theoretically possible due to the efficiency improvement, and 3) "ex post", i.e. actually realized by the efficiency improvement. Actual savings can be negative in case of backfire. Rebound mechanisms link the energy efficiency improvement to its actual impact on energy consumption.

the complexity and ambiguity. Section 3 describes the methodology and develops criteria for a rebound typology. Section 4 uses these criteria to analyze existing typologies, while Section 5 develops a new rebound typology. Section 6 discusses the usefulness of the typology and draws implications for future research and policy-making. Section 7 concludes.

2. Literature review

Publications on the rebound phenomenon now span about forty years. Most publications address the problems of quantifying rebound effects and identifying factors that determine their size. While initiated by Jevons [5], the beginning of today's rebound research is marked by Khazzoom [6–8] and Brookes [9,10], followed by an increasing number of publications. First *meta*-analyses of rebound research were published by Greening et al. [11,12]. During the past two decades, the number of journal articles published on the rebound phenomenon has increased immensely (see Fig. 2).

Fig. 2 shows the total number of peer-reviewed articles and discussion papers on the rebound phenomenon in the context of energy useas recorded on Web of Science. Note that the real dimension of the rebound literature (i.e. including grey literature, newspaper articles, etc.) is wider than the absolute numbers shown in Fig. 2. Nonetheless it illustrates the significant increase in scientific attention paid to the matter in the past 10 years. Note also that this review, as well as the entire article, is restricted to the energy rebound phenomenon, excluding the important work on climate and resource rebound effects and mechanisms [c.f. [13,14]].

Definitions of (energy) rebounds differ throughout the literature. Herring [15] focusses on the consumer level: "the 'rebound' or 'take-back' effect […] is how much of the energy saving produced by an efficiency investment is taken back by consumers in the form of higher consumption, both on the micro and macrolevel" (p. 2). Brookes [16] analyses the macro level, arguing that rebound effects occur when "economically justified improvements in energy efficiency may lead to higher-than-otherwise levels of consumption at the economy-wide level" (p. 356). Birol and Keppler [17] link the rebound effect to energy intensity and argue that "the rebound effect concerns changes induced by technological efficiency improvements themselves, which reduce the impact of these technical improvements on energy intensity" (p. 458).

We observe diverse and ambiguous terminology defining different types of rebound effects. For example, for entire economies, the terms macroeconomic, economy-wide and total rebound effect are used inconsistently. Economy-wide rebound(s) may refer to various rebound mechanisms beyond the micro level [e.g. [11], to the effect on economic growth [18] or to the total rebound effect in an economy [19–21]. Macroeconomic rebound effects can be several mechanisms at the macro level [22], or they can encompass everything but direct rebound effects [23]. A macro rebound effect may also refer to the entire effect for an economy [24]. The total rebound effect commonly refers to the entire rebound effect in an economy [25–27]. Sometimes, it also refers to the entire rebound effect at the global level [23]. Another example is the differentiation between direct and indirect rebound effects. While many use it to distinguish the effects on different types of goods and services (see Section 4.2), others define it differently, for example referring to the effects on single consumers via the effects on market expansion [28]. We find such ambiguous terminology throughout the literature (see Table 2 for a list of rebound mechanisms and definitions).

This heterogeneity also concerns empirical estimates of the rebound phenomenon for households, firms, sectors and at the macroeconomic level. As Gillingham [22] has pointed out, it is hard to clearly separate how much of the change in energy consumption can be causally attributed to rebound mechanisms and how much to other factors. Existing studies find the following: For the household level, recent *meta*-analyses show that the size of effects differs significantly between different goods, services and sectors [21,29–33]. Empirical work on firms is limited. Few studies assess rebound effects for single markets or sectors, with results ranging between 24% for the US manufacturing sector [34], 56–80% for the US residential sector [35], 75% for heavy industry in China [36] and 39% for an average of Chinese industrial sectors [37]. Moreover, two studies [38,39] find heterogeneous effect sizes for a range of sectors in the Norwegian and the US economies, respectively. It is hard to compare the results of these studies since research designs, data and the levels of aggregation differ greatly.

Several studies investigate economy-wide rebound effects using macroeconomic ex-ante models. Early publications appeared in the 1990s [40–42]. Later publications address the rebound phenomenon in relation to environmental policies [25,43–46]. A series of investigations examines an exogenous 5% increase in energy efficiency [47–50] with effect sizes ranging between 30% and beyond 100%, depending on the time horizon. Comparing eight Computational General Equilibrium (CGE) models, Allan et al. [51] find that the economy-wide rebound effect has a minimum of 37%. A more recent study combining econometric and Input-

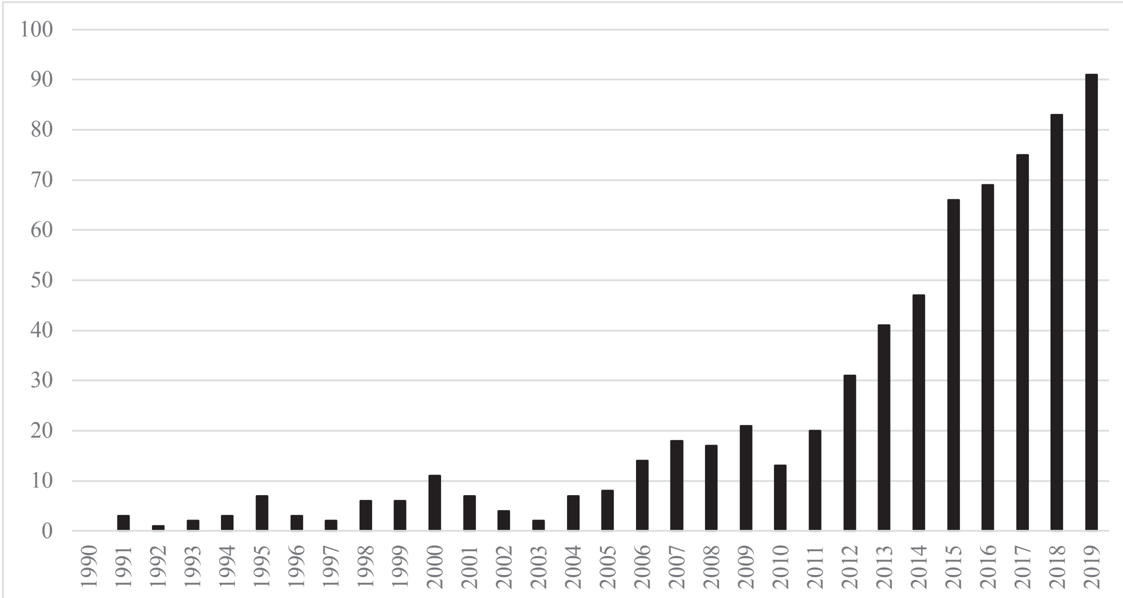

Fig. 2. Journal articles on energy rebound effects and mechanisms. Number of publications employing the term "Rebound" in combination with "energy efficiency", "energy saving*" or "energy conservation" in either title, abstract or keywords between 1990 and 2019. Results are limited to articles in peer-reviewed journals and discussion papers in English listed in the Science Citation Index Expanded (SCI-Expanded), the Social Science Citation Index (SSCI) or Emerging Sources Citation Index (ESCI).

Output analysis estimates the rebound effect in the EU as between 73% and 82% [52]. Few investigations go beyond the national level. With a CGE-model assessment, Koesler et al. [53] find that energy-efficiency improvements of 10% in German production correspond to an international rebound effect of 47%. Wei and Liu [54] estimate a CGE model for the global economy, with a 70% rebound effect for energy use and 90% for related emissions in 2040. Barker et al. [23] examine the global effects of efficiency policies and estimate a rebound effect of 31% by 2020 and 52% by 2030. Brockway et al. [55] employ an ecological economics perspective in choosing exergy as an efficiency metric to examine long-term national rebound effects in the UK, US and China. They find much higher effects (backfire) for China than the other two, which suggests that producer-sided economies are more rebound-prone. Comparing the studies is challenging because the investigations differ greatly in scope, datasets and in the selection of mechanisms and cause-effect-chains.

The field has reached a degree of maturity that, from our point of view, calls for an improved terminology and typology. The heterogeneity of the existing literature poses two interrelated challenges. First, several terms such as economy-wide rebound or indirect rebound effects are used inconsistently. Second, the confusion concerning such terms makes it difficult to relate estimates of the size of the rebound effect to the rebound mechanisms determining them. This in turn makes it difficult to devise political mitigation strategies that target the rebound mechanisms. In the following section, we propose a methodology to develop a novel typology with a clearly defined terminology. At the core of this proposed heuristic model is the differentiation between rebound mechanisms, which are the causal connections from energy efficiency improvements to energy demand, and rebound effects, which are the size of changes in such demand.

3. The methodology and criteria behind the typology development

Our methodology follows suggestions by Sovacool et al. [56], who state that social science contributions to energy research require a thorough drafting and application of socially relevant research questions, appropriate theory and conceptual frameworks, clearly stated research objectives and an explicit research design. Our research question is socially relevant as it addresses the environmentally important issue of the rebound phenomena and its containment via policies. Our approach engages with existing theories and typologies and in particular aims at developing them further. Our research objective is to provide a typology that incorporates the broad array of rebound mechanisms discussed in the literature. In terms of our research design, we analyze existing typologies and refine them based on explicitly developed criteria. In the following, we go further into these issues by developing a methodology particularly tailored for developing a systematic rebound typology.

The classification of objects is one of the fundamental problems in social science. According to Bailey [57], typologies are conceptually based whereas taxonomies are empirically derived. While the rebound literature uses both terms interchangeably (see for example Turner [4]), we use the term typology as our classification is conceptually based. The criteria guiding the classification process often remain unclear in other rebound publications. We develop quality criteria to evaluate classification schemes and to guide our typology development.

Classification generally aims to group elements into a property space by similarity. According to Kluge [58], the classes should assemble elements that are as similar as possible (internal homogeneity) and differ significantly across classes (external heterogeneity). However, evaluating similarities depends on having meaningful differentiations: Which properties of rebound mechanisms are relevant, considering the questions the typology intends to answer? Being transparent about the goals is important since the value of a typology needs to be assessed against these objectives. According to Bailey [57], successful classification means ascertaining the key dimensions of the classification. Therefore, clarity on the definition of elements and on the choice of dimensions is essential.

Bailey [57] further stresses two primary functions of classifications. First, classifications provide researchers with an exhaustive array of classes to describe the objects of interest. We relate to this function with the criterion of comprehensiveness. Collier et al. [59,60] emphasize the fundamental role of organized systems of types for measurement These systems form the basis for descriptive typologies that inform and structure quantitative analysis. A qualitative typology must be well-defined in the sense that no relevant mechanism is omitted or assigned to more than one category.

The second primary function of classifications is to serve as analytical tools to reduce complexity [57]; researchers need to simplify reality sufficiently to be able to understand it. At the same time, oversimplified classifications may obstruct the view for essential relations. A major challenge of classification is therefore to balance the goals of parsimony and informational value.

As argued in Section 1, key aims of rebound research are to determine the size of rebound effects and which rebound mechanisms cause them. Moreover, in light of the urgency of climate action, a major goal of studying the rebound phenomenon is to develop (policy) measures for reducing the rebound effect. Regarding informational value, a typology should thus also relate to levels of political governance concerned by the respective mechanism and its timing.

In view of the previous considerations regarding the purpose of a rebound classification, we put forward the following five quality criteria for a helpful rebound typology:

1. *Transparency of the development process (C1):* The reasoning behind the development of a typology needs to be explained to allow for critical objections and improvements. This transparency applies to the declaration of the purpose of the typology, the logical derivation of classes and the systematic assignment of the items (rebound mechanisms).
2. *Comprehensiveness (C2):* As a basic principle, types formed by the typology need to be mutually exclusive and collectively exhaustive [57,59]. The typology should integrate all relevant items unambiguously within its classes. In our case, the mechanisms identified in the literature need to be assignable to one specific type.
3. *Clarity (C3):* A typology needs to provide clear definitions, delimit the items that are to be classified and define the classes they are allocated to. Regarding a rebound typology, this relates to the clarity of the definitions of the rebound effect (as impacts of a subset of items), of the rebound mechanisms (as individual items located within a property space) and of the dimensions that form the property space (such as the economic level and time perspective).
4. *Parsimony (C4):* Parsimony in the strict sense means that “other things being equal – it is rational to prefer theories which commit us to smaller ontologies” [61]. However, there is often a trade-off between simplicity and the level of differentiation. For rebound typologies, this trade-off implies that the number of classes has to be low enough to enhance understanding and complex enough to grasp the important differences between the types of rebound mechanisms.
5. *Informational value (C5)*: To ascertain the key characteristics on which the classification is to be based, its central function must be kept in mind. In our view, a rebound typology should facilitate the analytical understanding of the rebound phenomenon as well as the development of policies to reduce them. This facilitation implies that the classes also need to relate to aspects that policy-makers can address. With regard to rebound mitigation, these could for instance be obligations bound to public incentives for efficiency improvements, mandatory efficiency standards for specific products or sectors, or economy-wide energy taxes.

We devise a conceptual classification and identify empirical examples of all classes. The process of developing our typology of rebound effects and mechanisms involved three steps. (1) Prominent existing typologies were analyzed against the five criteria. (2) Based on the results of this analysis, a novel typology was developed. (3) We then populated the typology with various rebound mechanisms encountered in the economic rebound literature.

4. Analysis of prominent rebound typologies

This chapter critically reviews prominent existing typologies of the rebound phenomenon. The by far most cited typology has been developed by Greening et al. [11], which we cover in Section 4.1. We sort the other prominent typologies into two groups. The first differentiates between direct and indirect effects (Section 4.2) and the second between different levels of aggregation (micro, macro and sometimes meso and/or global, Section 4.3). Table 1 gives an overview of the typologies included.

Table 1
Prominent rebound typologies analyzed for this article.

Author(s)	Year	Citations
Greening et al	2000	1968
Schipper and Grubb	2000	289
Sorrell	2007	831
Sorrell	2009	479
Madlener and Alcott	2009	240
Jenkins et al	2011	165
Maxwell et al	2011	41
Michaels	2012	17
Azevedo et al	2012	11
Gillingham et al	2014	342
Santarius	2016	26
Madlener and Turner	2016	12

4.1. An early contribution

In a prominent contribution, Greening et al. [11] distinguish four classes of effects: “(1) direct rebound effects, (2) secondary fuel use effects, (3) market-clearing price and quantity adjustments (especially in fuel markets) or economy-wide effects, and (4) transformational effects” (p. 390). Direct effects are due to the increased use of the energy service that has become more efficient. Secondary fuel use effects are similar to what is often called indirect effects, that is, “increases in demand for other goods and services” (p. 391). Economy-wide effects refer to a wide range of effects beyond direct and secondary effects that make up the effect on “total consumption and investment by both consumers and government” (p. 391). Finally, transformational effects leave the analysis of a static economy and look at changes in economic conditions such as consumer preferences.

The typology by Greening et al. was an important source in developing later typologies, especially the differentiation between direct and indirect effects. The typology is clear in the definition of its classes (C3) and allows for the allocation of many rebound mechanisms (C2). However, the paper also contains several shortcomings. In particular, it is not transparent about the way the four classes are derived (C1). There is no rationale of why these four classes are suggested. Neither is there a logic that connects the four classes (compared to the other taxonomies in sections 4.2 and 4.3, which develop classes according to product types of economic levels). In addition, having four classes does not allow for sufficient informational value (C4). Too many mechanisms are in one class: “[T]his distinction [between the four classes] is not entirely satisfactory. For example, economy-wide effects really cover all possible effects, on inputs, productivity, incomes, expenditures, prices and quantities” [62]. Finally, the classes do not relate directly to economic actors and are therefore inappropriate for policy development (C5).

4.2. Differentiation between product types: Direct and indirect

Sorrell [21] puts forward two classes: (1) direct and (2) indirect effects. They add up to the economy-wide effect. Direct effects refer to the increase of the goods or services that experience the increase in efficiency. Sorrell describes direct effects for both households and firms, each experiencing a substitution and an income/output effect (in our terminology, these are mechanisms – see Sub-section 5.3.1). Sorrell separates indirect effects into two major classes: embodied energy and secondary effects. Embodied energy is the energy needed to produce the capital for the increase in energy efficiency. Secondary effects range from changes in demand for other goods and services to decreasing overall energy prices. Sorrell [63] differentiates the short and the long run. He comes to the conclusion that the size of the total rebound effect can be “expected to increase in importance over time” (p. 1457).

The differentiation between direct and indirect effects has been taken up by various authors [29,30,64–66]. Their typologies entail direct and indirect rebound effects plus some additional class. They are called “‘macroeconomic’ rebound mechanisms” [30], “Economy wide rebound effect" [29,64] and "Economy-wide rebounds" [65]. Michaels additionally includes embodied energy as a fourth class.

Examining these typologies against the criteria from Section 3 yields similar results as Greening et al.'s typology. Most of the classes are clearly defined (C3) and many rebound mechanisms can be attributed to them (C2). However, the typologies suffer from several shortcomings. First, it is not transparent why the classes were chosen (C1). Second – as with Greening et al. [11] – the typologies do not facilitate enough differentiation (C4). In particular, there is usually one class that includes heterogeneous mechanisms. Turner [4] indicates another problem: "[T]he simplicity of Sorrell's typology means that it tends to be interpreted from the perspective of additive demand effects as the boundaries of the rebound effect increase" (p. 6). An example of this wrong interpretation is that firms produce more due to the 'output effect' and the effect of 'economy-wide productivity' increases leads to economic growth. However, economic growth is the sum of all increases of output of all firms. This misunderstanding is what we call the 'fallacy of double counting'. Finally, the classes make it difficult for policy-makers to build policies, as direct and indirect effects do not clearly relate to policy areas (C5). While being prominent in the literature, the differentiation between direct and indirect entails important shortcomings regarding the criteria for a rebound typology. Next, we discuss another type of classification that has received increasing attention in the past years.

4.3. Differentiation between economic levels: Micro, meso, macro and global

Several authors have put forward a different type of categorization along levels of economic action. Schipper and Grubb [67] distinguish between micro- and macroeconomic rebound effects. "Micro-effects" are "a direct 'feedback, within an activity or sector, between energy efficiency improvements and the level of energy-using activities". "Macro-effects" denote "the larger-scale interaction between more efficient energy use and economic growth" (p. 368). Madlener & Alcott [26] highlight that empirical analyses become increasingly complicated with higher levels of aggregation. Gillingham et al. [22] develop several macroeconomic rebound mechanisms (see Sub-section 5.3.3). Santarius [27] argues for introducing mesoeconomic effects as a third class, that is "effects that range from the level of the firm up to the level of a sector or market" (p. 407). Building on this, Madlener and Turner [19] put forward four analytical levels: The household and firm level (micro level), single sectors (meso level), the economy-wide min level (macro level) and economy-wide max level (global level).

These typologies are more transparent (C1) in explaining why they build the classes the way they do and the typologies generate more informational value regarding their specific goals (C5). The latter is achieved by shifting the perspective from goods (as in the direct/indirect typology) to actors. The actor-perspective captures the entities that create the rebound effect and determine its size. According to Santarius [27], "the distinction between micro-economic and macro-economic effects indicates the level of economic action at which rebounds are perpetuated either at the level of consumers (micro-economic rebound effects) or at the economy-wide level (macro-economic effects). This distinction therefore gives more scope to clarify the reasons and mechanisms why and how rebounds occur" (p. 406). Additionally, it boosts policy-relevance, as economic policies relate to the entities of this type of typology – households, firms, markets, sectors, national economies and international trade rules.

However, these approaches also have several downsides. First, the classes are often poorly defined (C3), which makes it unclear how to allocate mechanisms. For example, Madlener and Turner [19] refer to a list of 14 mechanisms in van den Bergh [62] but do not specify which mechanism falls into which class. Neither are the classes defined sufficiently clearly to allocate the mechanisms. Second, the typologies provoke treating mechanisms additively – the fallacy of double counting. The underlying problem is that classes are not mutually exclusive (C2). For example, Gillingham et al. [22] argue that additional spending of consumers and additional investments by firms are macroeconomic (growth) mechanisms. However, they are equivalent to the microeconomic income and output mechanism.

4.4. Summary

Existing typologies provide building blocks for a solid typology. Against the criteria of Section 3, however, they have several weaknesses. C1: Most typologies are not transparent regarding how they have been developed and in the choice of classes and dimensions (direct/indirect, micro/meso/macro). C2: All typologies seem to be exhaustive – meaning that all mechanisms can be attributed. However, classes are not always mutually exclusive as the same mechanism can be found in different classes (under different names). As a result, identical or overlapping mechanisms may be counted multiple times (fallacy of double counting). C3: Classes are seldomly clearly defined, which makes allocating mechanisms difficult (which might be one reason why it is hardly ever done). C4: The typologies are relatively simple. However, this comes at a cost. Often one class is very expansive so that it includes a highly heterogeneous array of mechanisms: 'economy-wide effects' in the case of Greening's contribution and 'indirect' or 'secondary effects' in the case of the typologies discussed in Section 4.2. The typologies of Section 4.3 are inconclusive in this regard, as the assignment of a large number of mechanisms to such typologies has not yet been attempted. Having one class that covers a large number of heterogeneous mechanisms makes it difficult to guarantee a sufficient degree of differentiation. C5: Under the premise of our definition of the purposes of research on the rebound phenomenon, the typologies differentiating between economic levels are more fruitful as they relate to different economic actors and policy arenas.

5. A rebound typology conceptualized along economic levels and time frames

Our critical review of prominent rebound typologies in Section 4 demonstrates the need for a transparent, comprehensive, clear and simple yet informative typology. The following proposed typology contains two heuristic dimensions: an economic level and a time dimension. The combination of these two dimensions yields eight classes, which allows for an exhaustive and more nuanced categorization compared to existing typologies. The typology distinguishes between rebound mechanisms and rebound effects. Fig. 3 provides a visual overview.

5.1. The crucial distinction between rebound mechanisms and rebound effects

Existing literature has rarely coherently distinguished between rebound effects and rebound mechanisms. The term rebound effect is commonly used for both the causal link between efficiency improvement and energy use as well as for the size of the impact. Sorrell [68] writes: "The "rebound effect" is an umbrella term for a variety of economic mechanisms that reduce the "energy savings" from improved energy efficiency. […] The rebound effect is commonly defined as the percentage of potential energy savings that are offset by these different mechanisms" (p. 2850). An exception is van den Bergh [62] who differentiates between the causal connections and the size. He uses the term "pathway". We use the term "mechanism" because it is common in

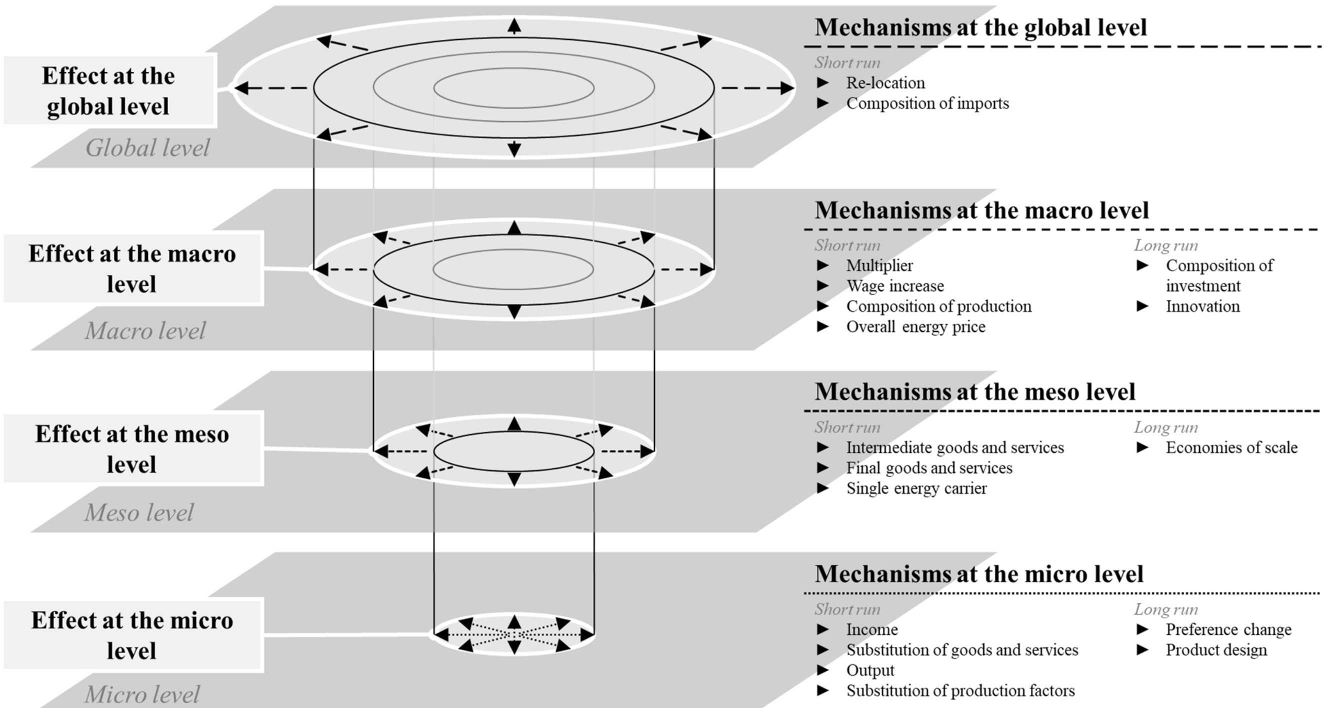

Fig. 3. Rebound effects and mechanisms at different economic levels and time frames. This figure provides an overview of the central categories in our typology. Four stacked analytical levels on which the rebound effect can be measured are distinguished. At each level, several rebound mechanisms, which are represented by the arrows, cause an increase in energy consumption. The respective types of mechanisms are categorized into short run and long run mechanisms. The connecting lines between the levels indicate that the rebound effect at a lower level is part of the rebound effect at a higher level.

the literature, albeit usually without an explicit distinction from the term “effect”. When we refer to the both rebound effects and mechanisms, we use the term rebound phenomenon.

The relation between rebound mechanisms and effects in our typology is as follows: An energy efficiency improvement triggers rebound mechanisms,[1] which result in a rebound *effect*. The rebound effect describes the size of the impact of an energy efficiency improvement in relation to its theoretical energy saving potential. It can be measured at different *levels* of aggregation – micro (firm or household), meso (market or sector), macro (national economy), or global (world economy). We therefore distinguish four rebound effects – one at each conceptual level. The often-used term economy-wide rebound effect is the rebound effect at the macro level.

In contrast, rebound *mechanisms* are causal connections running from energy efficiency improvements to energy demand. In other words, rebound mechanisms are the qualitative cause for how energy efficiency improvements increase energy consumption while the rebound effect is the quantitative measure of this (see Fig. 1). Similar to rebound effects, each rebound mechanism can be conceptualized at one of the four levels.

The impact of all relevant mechanisms contributes to the size of the rebound effect at the respective level of aggregation. However, effect size at a specific heuristic level is additionally influenced by mechanisms at lower levels. For example, efficiency improvements in car production can allow companies to increase profits and expand production (output mechanism, see Sub-section 5.3.1) – a mechanism at the micro level. When many firms introduce this new technology, price competition may lead to lower prices and, thereby, to higher sales (intermediate goods and services mechanism, see Sub-section 5.3.2) – a mechanism at the meso level. This mechanism at the meso level would not have taken place without the mechanism at the micro level. Mechanisms at higher levels can also impact a rebound effect at a lower level. With regard to the car example, an efficiency improvement can lead to decreasing energy demand at the macro level, which can result in a lower energy price in a competitive energy market (overall energy price mechanism, see Sub-section 5.3.3). This reduced price, in turn, further decreases the car manufacturer costs and may trigger additional expansion of production (output mechanism at the micro level). So, in other words, in our proposed typologies there are forward and backward linkages between the four heuristic levels.

5.2. Dimensions of classification: Economic levels and time frames

The first dimension of our classification is the economic level of aggregation. Structuring the typology along commonly used heuristic levels is particularly useful because they relate to economic theories, to empirical data and to potential policies to mitigate rebound. Economic theories often start by analysing actions of households and firms. While microeconomic theories commonly investigate the processes in single markets, macroeconomic theories usually cover economic variables at a country level. Data on economic output and energy consumption mostly exists on a firm, household, market, sector or country level, mainly because much of the empirical literature on rebound effects measures the rebound effect at these levels (see Section 2). Equivalently, policies commonly relate to markets, sectors or entire economies.

The *micro level* refers to households and firms. Rebound mechanisms at the micro level are initiated by an energy efficiency improvement in a firm or a household and are restricted to that single firm or household.

[1] We assume that the energy efficiency improvement is exogenously given and not induced by a policy. According to Gillingham (2016), policy-induced improvements are likely to lead to bundles of changes in product attributes. Such induced improvements are therefore even more difficult to capture analytically.

The *meso level* refers to a market or a sector.[2] All mechanisms that not only concern one agent but take place in a market or sector are mechanisms at the meso level. The *macro level* refers to a national economy. All mechanisms that do not only concern one sector or market are mechanisms at the macro level. The *global level* refers to the world economy. All mechanisms that not only concern the economy in which the energy-efficiency improvement takes place but also involve interactions between at least two economies are mechanisms at this level. At each of these levels, the size of the rebound effect can be measured.

The second dimension of classifying rebound mechanisms and effects is the time frame. Rebound mechanisms can be differentiated according to the time they take to impact energy demand [c.f. [11,21]]. Also, the size of the rebound effect depends on the time horizon investigated. However, existing typologies have not made the time frame an explicit classification dimension. Categorizing along time helps to improve research on understanding which mechanisms are responsible for the size of rebound effects because it relates to existing economic theories. Economic analyses typically differentiate between the short run and the long run. In the short run, prices, quantities and real income can typically change but economic conditions, e.g., preferences, technologies or the capital stock, stay the same. The long run includes changes of these economic conditions [70].

5.3. Systematic assignment of rebound mechanisms into the typology

In the following, we revisit a large number of rebound mechanisms from the literature and assign them to the classes of our proposed typology. We include the mechanisms from the typologies reviewed in Section 4. In addition, we include the mechanisms from two influential articles by van den Bergh [62] on rebound mechanisms in general and Koesler et al. [53] with a focus on the global level. Table 2 gives an overview of the rebound mechanisms. Tables 3, 4, 5 and 6 in the Appendix provide more details on how the mechanisms are defined in all articles covered. Fig. 3 depicts our proposed typology, combining the different levels with the mechanisms from the literature.

5.3.1. The micro level

Effects at the micro level are often divided into direct and indirect effects [21,63]. While we do not use this differentiation, we follow the literature in its differentiation between households and firms. In households, two short run mechanisms occur. First, households substitute the cheaper good or service for other goods or services (substitution of goods and services). Second, households experience an increase in income, leading to overall higher consumption of the goods or services (income). These mechanisms were described in almost all of the literature reviewed (see Table 3) with relatively coherent use of the terms substitution and income. These are short run mechanisms, as they relate to changes in incomes and prices and are therefore part of static analyses. The long run mechanisms are less commonly referred to in the literature, although they are already used in Greening et al. [11]. In the long run, consumer preferences can change due to more efficient technologies, which can affect both the composition and the quantity of consumption.

For firms, two short run and one long run rebound mechanisms can be distinguished. Firms make use of the energy efficiency improvement by expanding production. A detailed study of the literature shows that this output mechanism takes different forms. While some argue from a cost-perspective that firms use savings to expand production [11,21,63], others argue from a productivity perspective that firms can produce more by use of the same production factors [26,65]. The substitution of production factors mechanism describes how firms replace other production factors with energy services. We find that both mechanisms feature prominently in the literature reviewed, with seven publications citing both mechanisms and four publications addressing the substitution mechanism exclusively. Terminology is relatively homogenous (see Table 3). Both mechanisms occur in the short run as they are triggered by changes in (relative) prices. In the long run, firms can redesign the original product or some of its attributes [21], hence producing a product design mechanism [27,62]. For instance, car-manufacturers have continuously offset gains in fuel-efficiency by releasing new models, which are heavier, faster, etc., keeping fuel-consumption per kilometre roughly the same. This mechanism is less commonly described in the literature.

We decided to exclude what is commonly called embodied energy from the list of mechanisms. Embodied energy is the energy used to produce the technology that facilitates the energy efficiency improvement. There has been some discussion in the literature whether embodied energy effects classify as rebound mechanisms [13,27,71]. We follow the argument that embodied energy is not a rebound mechanism as it usually *precedes* an efficiency improvement, and rebound mechanisms are defined as a (causal) *result* of an efficiency improvement. Furthermore, we agree that the processes considered here are of technological nature and do not involve “any economic mechanism (…) [or] behavioural or systemic responses” [13,71].

5.3.2. The meso level

The meso level refers to sectors or markets. The literature exhibits three different areas in which mesoeconomic rebound mechanisms take place: final goods and services, intermediate goods and services, and (single) energy markets.

First, in final-goods sectors, a short run mechanism has the same origin as those mechanisms at the micro level. Firms lower their (energy-) costs by increasing energy efficiency. In the case of the output mechanism at the micro level, they use savings/higher productivity to expand production. However, an alternative or additional effect is to use lower costs to decrease the prices of final goods and services [19,21,64]. In a competitive market, this decrease lowers the market price of that respective good and consequently increases sales. Thus, the entire sector expands [17]. While certainly not apparent as often in the literature as many of the mechanisms described at the micro level, this is the most commonly mentioned mechanism at the meso level (for an overview, see Table 4).

Second, prices of intermediate goods and services can fall due to efficiency improvements in these sectors [11,27,64]. This fall may lead to one or both of the following rebound mechanisms that connect the intermediate and final-goods markets because the lower costs of intermediate goods or services lead to lower costs for producers in final-goods markets: producers can use lower expenses to increase production and/or, if the fall concerns many firms in a market or sector, they may decrease the price of the final good.

Third, a mesoeconomic rebound mechanism can be triggered by a downward pressure on the price of a single energy carrier, which can result from less energy being consumed due to energy efficiency increases [27,65]. Various energy markets exist (e.g., for oil, petrol, gas, coal, lignite, electricity, etc.). Whenever a significant number of firms in a sector using one such energy carrier increases energy efficiency, demand for that type of energy carrier decreases. Depending on the elasticity of supply of that energy carrier vis-à-vis other energy carriers, the price will decrease [72], which encourages other users of the energy carrier to consume more. Consequently, demand for the energy carrier will be larger than what would be expected from the efficiency improvements alone [27].

The three mechanisms mentioned so far take place in the short run as they relate to changes in prices. At the meso level, the literature reveals one mechanism in the long run as well. Scaling up the production to meet higher demands may induce economies of scale, which will lead to

[2] According to the OECD [69] a market can refer to either a specific product or a geographical area. We refer to product markets. A sector can have many different meanings. We refer to “a subgroup of an economic activity” (p. 609), meaning a group of firms that produce similar goods or services.

Table 2
Summary table of rebound mechanisms identified in the literature review.

Mechanism	Author (s)	Greening et al 2000	Schipper and Grubb 2000	Sorrell 2007	Sorrell 2009	Madlener and Alcott 2009	Van den Bergh 2011	Jenkins et al 2011	Maxwell et al 2011	Michaels 2012	Azevedo et al 2012	Gillingham et al.2016	Santarius 2016	Madlener and Turner 2016	Koesler et al 2016
Substitution of goods and services	Micro level	x	x	x	x	x	x	x	x		x	x	x	x	
Income		x	x	x	x	x	x	x	x		x	x	x	x	x
Preference change		x				x	x				x			x	
Output		x		x	x	x		x		x			x		
Substitution of production factors		x	x		x	x	x	x		x			x	x	x
Product design							x						x		
Final goods and services	Meso level			x					x					x	
Single energy carrier				x						x			x		
Intermediate goods and services		x							x				x		
Economies of scale													x		
Overall energy price	Macro level		x	x	x	x	x	x							
Composition of production				x	x		x	x					x		
Composition of investment			x									x			
Multiplier								x				x			
Innovation							x					x			
Wage increase													x		
Re-location	Global level						x		x						x
Composition of imports															x

Table 3
Mechanisms on the micro level identified in literature review.

Author(s)	Year	Micro level Substitution of products	Income	Preference change	Firm output	Substitution of production factors	Product redesign
Greening et al	2000	p. 390: If the price of the energy service drops, consumers should substitute indefinitely for a given energy service	p. 390: the direct effect of a price reduction may be decomposed into a substitution effect and an income effect	p. 391: Changes in technology also have the potential to change consumers' preferences (…).	p. 390: a technological improvement (…) reduces the price of energy services (…) and should theoretically increase the supply.	p. 391: if energy services decrease in effective price, a firm will substitute energy services for other factor inputs.	
Schipper and Grubb	2000	p. 4: a substitution effect, whereby consumption of the (cheaper) energy (…) substitutes for the consumption of other goods and services	p.4: an income effect, whereby the increase in real income (…) allows a higher level of utility (…) by increasing consumption (…)		p. 4: output effect [:] (…) cost savings (…) allows a higher level of output (…) - thereby increasing consumption of all inputs		
Sorrell	2007	p. 1457: (…) energy-efficiency improvements (…) will reduce the cost of energy-intensive goods and services (…) thereby encouraging consumer demand to shift towards [them]	p. 1457: (…) money saved (…) may be spent on other goods and services that also require energy to provide.		p. 1457: Output effects: Producers may use the cost savings (…) to increase output	p. 1462: Since energy prices were falling (…), energy substituted for other factors of production	
Sorrell	2009	p. 7: (…) consumers will substitute towards the more energy-efficient product [… and] away from other now relatively more expensive goods.	p.7: (…) the lower effective price for the energy service (…) means consumers will (…) increase consumption of the more energy-efficient product (…) [and] other normal goods.				
Madlener and Alcott	2009	p. 368: product substitution [:] (…) a consumer demands more of a given energy-service or product because it becomes cheaper	p. 368: income effect to consumers, which may be called the 're-spending effect			p. 368: (…)higher effciency (…) leads to substitution of more energy for other factors of production.	
Van den Bergh	2011	p. 371: substitution effect: (…) we will consume more of those goods and services that are now produced in a more energy- efficient way.	p. 371: income effect: (…) the quantities to consume have become cheaper per unit, and we can buy more of the same products, or other products,	p. 371: consumer preferences may also change due to improvements in energy efficiency (…)	p. 371: (…) energy 'freed' from producing the previous level of output (…) is available (…) for some additional production.	p. 371: (…) the substitution of energy for other factors of production.	
Jenkins et al	2011	p. 47: More intensive use of energy-consuming equipment (…) because of (…) lower effective energy cost	p. 47: 3. Re-spending of financial savings due to energy conservation on other (…) goods and services (income effects).	p. 47: 12. Changes in the cost of energy (…) may stimulate changes in preferences.		p. 47: energy efficiency (…) change (…) the factor input mix (…) in production, due to substitution (…) relationships.	p. 47: Purchase of larger units or units with more functions/services and consequently using more energy
Maxwell et al	2011	p.13: substitution effect: consumers may respond to the lower (…) price (…) by substituting that energy service for (…) other goods and services	p. 13: income effects: (…) consumers may respond to the increase in apparent income by increasing demand for that energy service		p. 13: output effects: (…) producing firms may (…) respond by increasing use of that energy service to expand their output	p. 13: substitution effects: (…) firms may (…) substitute the now-cheaper energy service for other inputs to production	
Michaels	2012	p. 407: (…) direct rebounds (…) arise from the (…) substitution effect on the consumer side	p. 406: (…) consumers use the extra relative income or the reduced prices (…) to demand more of the same (…) or (…) other goods and services		p. 407: output effect on the production side (…), equivalent to the income effect on the consumption-side	p. 407: substitution effect[:] the more efficient use of energy results in firms substituting (…) other (…) resources with increased energy use.	p. 408: firms can also generate a rebound effect (…) [by] redesigning the original product (…)
	2012						

(continued on next page)

Table 3 (*continued*)

Author(s)	Year	Micro level Substitution of products	Income	Preference change	Firm output	Substitution of production factors	Product redesign
Azevedo et al		p. 34: The substitution effect (…) measures the degree of substitutability (…) or complementarity (…) between products.	p. 33: (…) surplus of disposable income could be spent on increasing the level of service required (…) or/and allocated to other additional goods and services				
Gillingham et al.	2016	p. 21: price effect	p. 21: respending (income effect);	p.22: changes in preferences;		p. 21: change in factor input mix	
Santarius	2016				p. 8: Output or scale effects. If an input's productivity increases, (marginal) production costs may fall at each level of output.	p. 8: "direct substitution". If fuel is substitutable for other inputs,(…) production (…) will use (…) more fuel and (…) less of other inputs	
Madlener and Turner	2016	p. 9: Substitution effect: Efficiency gains in a particular energy service lead to […] more consumption of that service and out of other goods and services.	p. 9: (…) additional income (…) freed up by saving energy costs can be used for other (…) consumption.	p. 9: Substitution and income effects may lead to overall changes in consumption patterns.			p. 8: Output or scale effects. If an input's productivity increases, (marginal) production costs may fall at each level of output.
Koesler et al	2016		p. 445: We expect real household income to rise (…), thereby increasing rebound			p. 445: substitution effect: (…) there is substitution towards energy (…) in production in the target sector	

Table 4
Mechanisms on the meso level as identified in literature review.

Author(s)	Year	Meso level Prices of final goods and services	Price of a single energy carrier	Prices of intermediate goods and services	Economies of scale
Greening et al	2000			p. 391: secondary effects result from (…) lower cost of one sector's output on production costs of other sectors.	
Sorrell	2007	p. 2: Large-scale reductions in energy demand may translate into lower energy prices (…).	p. 2: (…) energy efficiency improvements (…) will reduce the price of energy (…) encouraging (…) demand to shift towards [them].		
Maxwell et al	2011	p. 37: Under energy efficiency (…) products/services (…) become cheaper and consumer demand grows.		p. 37: Substitution effect (…) allows the price of output in (…) other sectors that purchase it as inputs to their sectors to fall.	
Michaels	2012		p.8: Technology diffusion: (…) lower fuel use could decrease [energy] price and indirectly affect its use in the other sectors.		
Santarius	2016		p. 409: (…) [because] consumers and firms demand less of a particular form of energy, its price will fall (in relative terms).	p. 411: An efficiency gain in any one industry reduces (…) the cost of intermediate inputs to other industries	p. 410: increased demand (…) can result in economies of scale that again cause prices to fall and produce a (…) relative income gain
Madlener and Turner	2016			p. 391: secondary effects result from (…) lower cost of one sector's output on production costs of other sectors.	

lower prices and increased production. With only one reference [27], this mechanism is the least prominent in the literature reviewed.

5.3.3. *The macro level*

At the macro level, we find six mechanisms, four related to the short and two related to the long run. Table 5 sums up the findings from the literature review. The overall energy price mechanism is similar to the *price of a single energy carrier* mechanism and occurs in the short run as it relates to price changes. If energy efficiency increases for many actors (households and/or firms), overall demand for energy decreases.

Table 5
Mechanisms on the macro level as identified in literature review.

Author(s)	Year	Macro level Overall energy price	Production-composition	Investment-composition	Multiplier	Innovation	Wages
Schipper und Grubb	2000	p. 368: (…) re- strained (growth in) energy use may be expected to (…) keep energy price increases lower		p. 368: (…) structural change (…) if energy-intensive sectors or activities were stimulated			
Sorrell	2007	p. 2: Large-scale reductions in energy demand may translate into lower energy prices (…).	p. 2: (…) energy efficiency improvements (…) will reduce the price of energy (…) encouraging (…) demand to shift towards [them].				
Sorrell	2009	p. 1457: Energy market effects: (…) reductions in energy demand may translate into lower energy prices	p. 1457: Composition effects: (…) energy efficiency improvements (…) will reduce the price of energy (…) encouraging (…) demand to shift towards [them].				
Madlener and Alcott	2009	p. 371: (…) lowered demand for energy inputs (…) leads to a fall in the unit price of energy (…)					
Van den Bergh	2011	p. 47: (…) initial energy savings (…) [can be] so large that the energy price (…) drop[s]	p. 47: Interactions between (…) markets due to the changing efficiency (…). As a result, the composition of production (…) will be affected			p. 47: Technological innovation and diffusion effects will occur through (…) investments in R&D (…)	
Jenkins et al	2011	p. 22: Market Price Effects: Widespread improvements in energy efficiency can (…) decrease (…) energy market prices	p. 22: “Composition Effects”: improvements in energy efficiency (…) [may] shift (…) the composition of the economy towards energyintensive sectors.		p. 23: “Economic Growth Effect”: (…) lower costs for energy (…) will (…) increase (…) real incomes, (…) investment and consumption, stimulating economic growth.		
Gillingham et al.	2016			p. 22: (…) sectoral reallocation may occur due to a change in the relative returns of economic sectors.	p. 22f: dollars that were previously spent on energy can now be spent in ways that engage “new” economic activity […, which] may […] exceed the initial amount by some multiplier	p.22: a zero- cost breakthrough in one sector may spill over to others	
Santarius	2016		p. 409: ‘composition effect’ (…) Reduced market prices can (…) alter the composition (…) of (…) a country’s economy.				p. 411: firms can use the additional profit (…) to raise workers’ wages
Madlener and Turner	2016	p. 21: price effect	p. 21: respending (income effect);	p.22: changes in preferences;		p. 21: change in factor input mix	

Depending on the elasticity of energy supply, this decrease leads to a lower price for and a greater use of energy [21,26,30,62,63,67]. The overall energy price mechanism relates to several or all sources of energy (compared to the price of a single energy carrier mechanism at the meso level). Second, there is a macroeconomic multiplier mechanism of efficiency improvements [22,30], which starts from the same logic as the income mechanism at the micro level. These household expenditures translate to increased revenues for the producers (employers and employees), which in turn translate into more investment and spending. This way, the multiplier mechanism traverses the economy [22,72]. It follows the logic of the traditional multiplier effect prominently argued for by Keynes [73] and is part of most macroeconomic textbooks. The macroeconomic rebound multiplier is different from the traditional multiplier in that additional demand does not stem from additional government investment [22,72].

A similar mechanism unfolds via wage increases [27]. As Wackernagel and Rees [74] note, profits from efficiency improvements may also be allocated to raise employees’ wages. We identify this as a macroeconomic rebound mechanism as people spend their wages on a wide basket of goods. It is a long run rebound mechanism as firms are unlikely to convert cost savings instantly into higher wages. Allan et al. [47] model that this way of transferring potential rebound mechanisms from

Table 6
Mechanisms on the global level as identified in literature review.

Author(s)	Year	Global level Re-location	Imports
Maxwell et al	2011	p. 38: (…) rebound effects can impact trade patterns (…)	
Van den Bergh	2011	p. 47: International trade and re-location effects of changing efficiency (…) affect[s] comparative advantages.	
Koesler et al	2016	p. 446: if the price falls in a particular home sector, (…) the competitiveness of the corresponding sector in other countries will fall (…)	p. 446: (…) if (…) home-country import demand changes for non-price reasons, this affects the export demand in foreign countries.

the production- to the consumption-side may reduce the net economy-wide rebound.

Note that, although the macroeconomic multiplier mechanism and the wage increase mechanism are separate mechanisms, both refer to increases in consumption due to higher incomes. While, in the case of the macroeconomic multiplier mechanism, the increase in income stems from more sales, for the wage increase mechanism, it stems from cost savings. Note also that deciding whether these two mechanisms take place in the short or long run is difficult. We assign them to short run because they do not change economic conditions such as preferences, technologies, etc. However, it could also be argued that these mechanisms take a significant time to unfold in the real world and could therefore be labelled long run.

If efficiency improvements particularly affect energy intensive goods or services, they can induce a demand shift towards more energy intensive goods or services [21,27,30,62,63]. Building on the terminology in the literature, we label this the composition of production mechanism. It is again difficult to consistently assign this mechanism to the short or the long run. While neoclassical theories often assume an instantaneous reassignment of production factors, such changes are likely to take significant time in the real world.

A related mechanism occurs clearly in the long run. The composition of investment mechanism is mediated by investment patterns [22,67]. As energy inputs in energy-intensive sectors become more productive due to efficiency gains, relative returns on investment for that sector also increase. Hence, investments relocate, and the sector will grow relative to others in the long run. A second long run mechanism at the macro level relates to innovation. The literature argues that technologies associated with energy efficiency improvements may spur additional innovations (see Table 5). This effect can have different causes: The new technologies spill over into other sectors [22], the policy leading to the energy efficiency improvement also triggers other innovations (ibid.), the new technology may generate ideas for additional energy-saving technologies [65] or the change in energy prices induced by more efficient technologies leads to additional investments in developing more efficient technologies [62]. As innovations take time to unfold and change economic conditions, this is a long run mechanism.

We excluded one mechanism referred to in the literature: total factor productivity. It is sometimes argued that energy efficiency improvements trigger overall increases in productivity [21,62]. However, this is an example of a fallacy of double counting: Since all reasons for an increase in total factor productivity are already covered by other mechanisms – in particular investments in new technologies and innovations – increases in total factor productivity must not be included as a separate mechanism. If there are further mechanisms contributing to total factor productivity, these should be made explicit as separate mechanisms.

5.3.4. The global level

Energy efficiency improvements in one country also affect energy consumption in other countries. We follow Sorrell [21] who states: “To capture the full range of rebound effects, the system boundary for the independent variable (energy efficiency) should be relatively narrow, while the system boundary for the dependent variable (energy consumption) should be as wide as possible” (p. 15). We therefore define a narrower system boundary for energy efficiency by only looking at efficiency improvements and subsequent rebound mechanisms originating within one country – thereby excluding rebound mechanisms originating in other countries. Table 6 gives an overview of the mechanisms found in the literature.

The most prominent global mechanism is the re-location mechanism: Efficiency improvements in firms in one country raise their competitiveness compared to firms in other countries [53,62]. As a result, trade patterns change and markets shift towards these efficiency first-movers [64]. From the perspective of the home country, the rebound effect may therefore appear to be larger than from a global perspective. In other countries, the increase in efficiency leads to a decrease of the domestic energy consumption [53]. Van den Bergh [62] coined this mechanisms “re-location” (p. 47). As Koesler et al. [53] point out, this mechanism works not only via the demand for final goods and services but also via the accompanying demand for intermediate goods and services. A second global mechanism turns to the demand side of the economy. Koesler et al. [53] show how efficiency changes in the home-country may reshape the amount and composition of imports. This reshaping alters production and therefore also energy consumption in other countries. Contrary to rebound mechanisms on the other economic levels, it is unclear for both global mechanisms whether they increase or decrease energy consumption [53]. The two mechanisms are categorized as short run as the change in production takes place using existing capital equipment and workers and can be modelled in a static environment. However, there might also be long run implications.

6. Discussion

The literature review in Section 2 shows that a major challenge in the flourishing literature on rebound effects is the lack of a shared understanding of central terms and mechanisms and the relation between theoretical and empirical research. Section 4 shows that a contributing factor to this challenge is the absence of a shared typology and that existing typologies are not transparent, making it difficult to use and improve them. The typology developed in Section 5 aims to alleviate these challenges. From our perspective, the typology provides a solution to Turner’s [4] refutation to presenting ever-new rebound typologies, as more rebound mechanisms will be found over time. If future research follows our suggestion that there are but *four rebound effects*, one for each of the *four heuristic levels*, it can flourish and add more *rebound mechanisms* without rendering our typology obsolete. The discussion of our typology’s merits and limitations is structured along the five criteria for typologies developed in Section 3.

Transparency: Our typology is explicit in its purposes and how it has been developed. This transparency facilitates future research in improving and/or criticizing the typology. Making the purposes explicit – namely understanding the determinants of rebound effects and developing policies to limit them – has strongly influenced the typology’s development. Most importantly, it has shaped the choice of dimensions. This choice has led to the exclusion of the dimension ‘product types’ – i.e. distinguishing between direct and indirect effects. While this distinction between direct and indirect effects is well established in the literature (e.g. [21]), we propose that its continued use would be unhelpful for both future research and policy making because it does not relate to common economic theories, existing data or policy arenas. It is our impression that the differentiation results from the historic development of rebound literature that, for a long time, focused on households’ behaviors. With a broadening of research, the distinction between different economic levels has become more productive in helping structure research.

Comprehensiveness: In Section 4, we argued that existing typologies already facilitated classes for the diversity of rebound mechanisms. However, the typologies did not allocate a comprehensive list of mechanisms. Our allocation in Section 5.3 is therefore novel. The only other such attempt has been conducted by Colmenares et al. [75]. They assign a large number of effects from the literature into a typology of four classes. However, they do not make transparent how they have allocated the mechanisms. Another advantage of stringent definitions and allocation of our typology is that it helps to keep the classes mutually exclusive. It has been pointed out that there are overlaps between different mechanisms from the literature – what we call the the 'fallacy of double counting'. This overlap has become visible whenever mechanisms appeared in different classes that referred to the same underlying processes.

This comprehensiveness criterion has led to three mechanisms being excluded from our list. First, total factor productivity has not been included because its underlying processes are already covered by other mechanisms (see Sub-section 5.3.3). Similarly, several mechanisms referring to relationships between energy efficiency improvements and economic growth have been excluded. For example, van den Bergh [62] argues that "[c]apital investment and accumulation effects of changes in energy costs mean long term effects on production output and productivity, which will affect energy use" (p. 47). However, such investments and accumulation and their effects on output and productivity are already covered by the mechanisms 'output', 'investment' and 'innovation' of our typology. A third mechanism mentioned in the literature but excluded in our list is the "general equilibrium or macroeconomic effect" [19,62]. It covers a large number of processes included in other mechanisms in our list.

Apart from these three exceptions, it has been possible to accommodate into the typology all rebound mechanisms which we have identified in the economic literature on rebound effects in seminal peer-reviewed papers. We believe a promising next step would therefore be to investigate whether the typology can be challenged by or enriched with mechanisms from the growing body of research on the rebound phenomenon particularly from other disciplines such as sociology, psychology or physics [see several contributions in [76], as well as [77–80] and others]. An additional promising next step would be to connect it to the debate on the sufficiency rebound phenomenon [81].

Clarity: The classes of the typology have been clearly defined. Of particular importance is the differentiation between rebound mechanisms and rebound effects. This differentiation allows the typology to be related more directly to theoretical and empirical research: While theoretical discussions are mainly concerned with how rebound mechanisms cause a change in energy consumption, empirical research investigates the size of rebound effects on the different economic levels. The distinction between effects and mechanisms has also led to the exclusion of direct and indirect rebound effects from the typology as these are not mechanisms. Additionally, embodied energy in household appliances and capital equipment have been excluded as these occur prior to the energy efficiency improvements and therefore do not fall into our definition of mechanisms. While this distinction brings clarity into the debate, it also indicates a crucial limitation within rebound research in general: it is very difficult to empirically estimate the importance of a specific rebound mechanism.

Parsimony: We argue in Section 4 that existing typologies are often simple but lack a sufficient degree of differentiation between classes. In particular, many typologies have one class that incorporates a large number of rebound mechanisms, preventing facilitation of a meaningful analytical basis. By combining the dimensions of economic level with time frames, a higher degree of differentiation has been achieved.

Information value: The two dimensions of economic level and time frame improve the foundation for future theoretical and empirical research as they relate to existing economic theories and empirical data. In addition, our typology provides a more nuanced starting point for developing policies that tackle rebound effects compared to previous attempts (cf. Font Vivanco et al. [82], who are relatively broad brushed, focusing on efficiency, consistency and sufficiency strategies, or van den Bergh [62], who focusses on well-known generic economic instruments for internalizing environmental externalities). Our typology makes it clear that policies should not aim at tackling the rebound effects *per se* but should focus on specific mechanisms. Allocating mechanisms to each level allows policy makers to ensure they address the relevant mechanisms at play.

7. Conclusions

Over the last 40 years, a substantive literature on the rebound phenomenon has emerged. However, the burgeoning literature lacks a shared foundation of definitions, classifications and lists of important mechanism. This lack makes it difficult to compare and contrast findings, aggregate results and provide policy recommendations.

While there are a variety of existing classifications of rebounds effects, few articles have focused on developing coherent and transparent typologies. This paper aims to advance the foundations of such a typology by systematically building on existing typologies and being clear in its definitions and its development. We see our attempt as a step towards developing a shared typology as envisaged by Dunlop [3]. A possible next step would be to challenge or advance this typology by attempting to incorporate non-economic rebound mechanisms and to see in how far and in what ways it would need to be adjusted. It is our hope that the transparency of our approach will provoke further critical debate within the community, at the end of which some form of agreed typology could emerge.

From our perspective, a widely shared typology could then increasingly inform and integrate empirical and theoretical research. Such a basis is urgently needed for policy makers since few energy efficiency programs take the rebound phenomenon into account [83,84]. This omission is partly due to the lack of systematic understanding of what these effects are but also due to influential interest groups [85]. It is especially important that policy makers better understand the way various rebound mechanisms work so that they can develop suitable policy mixes to mitigate rebound effects.

In future research, the typology could be set in relation to certain policies and thereby help structure policy proposals and develop new policy ideas. It could be a tool to anticipate ex ante the effectiveness of certain rebound mitigation policies. In that sense, our typology could provide a 'check list' for policy makers, one that empowers them to design a comprehensive and 'rebound-proof' energy efficiency policy mix [86].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] IPCC, Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, IPCC, Geneva, Switzerland, 2018.

[2] International Energy Agency (IEA), World Energy Outlook, OECD Publishing, France, Paris, 2019, p. 2019.
[3] T. Dunlop, Mind the gap: a social sciences review of energy efficiency, Energy Res. Soc. Sci. 56 (2019) 101216. https://doi.org/10.1016/j.erss.2019.05.026.
[4] K. Turner, 'Rebound'effects from increased energy efficiency: a time to pause and reflect, Energy J. 34 (2013) 25–34, https://doi.org/10.5547/01956574.34.4.2.
[5] W.S. Jevons, The Coal Question: An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal Mines, 2nd ed., Macmillan and Co, London, 1865.
[6] J.D. Khazzoom, Energy savings from more efficient appliances: a rejoinder, Energy J. 10 (1989) 157–166.
[7] J.D. Khazzoom, Energy saving resulting from the adoption of more efficient appliances, Energy J. 8 (1987) 85–89.
[8] J.D. Khazzoom, Economic implications of mandated efficiency in standards for household appliances, Energy J. 1 (1980) 21–40.
[9] L. Brookes, The greenhouse effect: the fallacies in the energy efficiency solution, Energy Policy. 18 (1990) 199–201.
[10] L. Brookes, Energy policy, the energy price fallacy and the role of nuclear energy in the UK, Energy Policy. 6 (1978) 94–106, https://doi.org/10.1016/0301-4215(78)90031-9.
[11] L.A. Greening, D.L. Greene, C. Difiglio, Energy efficiency and consumption: the rebound effect a survey, Energy Policy. 28 (2000) 389–401, https://doi.org/10.1016/S0301-4215(00)00021-5.
[12] L.A. Greening, D.L. Greene, Energy use, technical efficiency, and the rebound effect: a review of the literature, in: . in: Exp. Freer Mark. (Ed.), Lessons Last 20 Years Prosepects Future, International Association for Energy Economics, 1998.
[13] D. Font Vivanco, W. McDowall, J. Freire-González, R. Kemp, E. van der Voet, The foundations of the environmental rebound effect and its contribution towards a general framework, Ecol. Econ. 125 (2016) 60–69, https://doi.org/10.1016/j.ecolecon.2016.02.006.
[14] F. Figge, C.W. Young, R. Barkemeyer, Sufficiency or efficiency to achieve lower resource consumption and emissions? The role of the rebound effect, J. Clean. Prod. (2014) 216–224, https://doi.org/10.1016/j.jclepro.2014.01.031.
[15] H. Herring, Does energy efficiency save energy: the implications of accepting the Khazzoom-Brookes Postulate, Open University, Energy and Environment Research Unit, Milton Keynes, UK, 1998.
[16] L. Brookes, Energy efficiency fallacies revisited, Energy Policy. 28 (2000) 355–366, https://doi.org/10.1016/S0301-4215(00)00030-6.
[17] F. Birol, J.H. Keppler, Prices, technology development and the rebound effect, Energy Policy. 28 (2000) 457–469, https://doi.org/10.1016/S0301-4215(00)00020-3.
[18] C. Paul, A.-K. Techen, J.S. Robinson, K. Helming, Rebound effects in agricultural land and soil management: review and analytical framework, J. Clean. Prod. 227 (2019) 1054–1067, https://doi.org/10.1016/j.jclepro.2019.04.115.
[19] R. Madlener, K. Turner, After 35 Years of Rebound Research in Economics: Where Do We Stand?, in: T. Santarius, H.J. Walnum, C. Aall (Eds.), Rethink. Clim. Energy Policies, Springer International Publishing, Cham, 2016: pp. 17–36. https://doi.org/10.1007/978-3-319-38807-6_2.
[20] E. Rosenbaum, Rebound effects and green growth–An examination of their relationship in a parsimonious equilibrium input-output-framework, J. Clean. Prod. 225 (2019) 121–132, https://doi.org/10.1016/j.jclepro.2019.03.296.
[21] S. Sorrell, The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency, UK Energy Research Centre London, London, UK, 2007.
[22] K. Gillingham, D. Rapson, G. Wagner, The Rebound Effect And Energy Efficiency Policy, Rev. Environ. Econ. Policy. 10 (2016) 68–88, https://doi.org/10.1093/reep/rev017.
[23] T. Barker, A. Dagoumas, J. Rubin, The macroeconomic rebound effect and the world economy, Energy Effic. 2 (2009) 411–427, https://doi.org/10.1007/s12053-009-9053-y.
[24] L. Wu, Y. Chen, M.R. Feylizadeh, W. Liu, Estimation of China's macro-carbon rebound effect: method of integrating data envelopment analysis production model and sequential Malmquist-Luenberger index, J. Clean. Prod. 198 (2018) 1431–1442, https://doi.org/10.1016/j.jclepro.2018.07.034.
[25] T. Barker, T. Foxon, The macro-economic rebound effect and the UK economy, 4CMR, Cambridge, UK, 2006.
[26] R. Madlener, B. Alcott, Energy rebound and economic growth: A review of the main issues and research needs, Energy. 34 (2009) 370–376, https://doi.org/10.1016/j.energy.2008.10.011.
[27] T. Santarius, Investigating meso-economic rebound effects: production-side effects and feedback loops between the micro and macro level, J. Clean. Prod. 134 (2016) 406–413, https://doi.org/10.1016/j.jclepro.2015.09.055.
[28] C. Wang, P. Nie, How rebound effects of efficiency improvement and price jump of energy influence energy consumption? J. Clean. Prod. 202 (2018) 497–503, https://doi.org/10.1016/j.jclepro.2018.08.169.
[29] I.L. Azevedo, M. Sonnberger, B.A. Thomas, G. Morgan, O. Renn, The Need to Account for Consumer Behaviour in order to Develop Robust Energy Efficiency Policies. A review of the literature on the rebound effect in energy efficiency and report from expert workshops, International Risk Governance Council, Lausanne, Switzerland, 2012.
[30] J. Jenkins, T. Nordhaus, M. Shellenberger, Energy emergence: rebound and backfire as emergent phenomena, Breakthrough Institute, Oakland, CA, 2011.
[31] R. Madlener, B. Alcott, Herausforderungen für eine technisch-ökonomische Entkoppelung von Naturverbrauch und Wirtschaftswachstum unter besonderer Berücksichtigung der Systematisierung von Rebound-Effekten und Problemverschiebungen, Deutscher Bundestag, Enquete-Kommission Wachstum, Wohlstand, Lebensqualität, Zürich, 2011.
[32] V.V. Munyon, W.M. Bowen, J. Holcombe, Vehicle fuel economy and vehicle miles traveled: an empirical investigation of Jevon's Paradox, Energy Res. Soc. Sci. 38 (2018) 19–27, https://doi.org/10.1016/j.erss.2018.01.007.
[33] R.B. Mitchell, R. York, Reducing the web's carbon footprint: does improved electrical efficiency reduce webserver electricity use? Energy Res. Soc. Sci. 65 (2020), 101474 https://doi.org/10.1016/j.erss.2020.101474.
[34] J. Bentzen, Estimating the rebound effect in US manufacturing energy consumption, Energy Econ. 26 (2004) 123–134, https://doi.org/10.1016/S0140-9883(03)00047-1.
[35] L. Orea, M. Llorca, M. Filippini, A new approach to measuring the rebound effect associated to energy efficiency improvements: an application to the US residential energy demand, Energy Econ. 49 (2015) 599–609, https://doi.org/10.1016/j.eneco.2015.03.016.
[36] B. Lin, J. Li, The rebound effect for heavy industry: empirical evidence from China, Energy Policy. 74 (2014) 589–599, https://doi.org/10.1016/j.enpol.2014.08.031.
[37] Y.-J. Zhang, H.-R. Peng, B. Su, Energy rebound effect in China's Industry: an aggregate and disaggregate analysis, Energy Econ. 61 (2017) 199–208, https://doi.org/10.1016/j.eneco.2016.11.011.
[38] S. Grepperud, I. Rasmussen, A general equilibrium assessment of rebound effects, Energy Econ. 26 (2004) 261–282, https://doi.org/10.1016/j.eneco.2003.11.003.
[39] H.D. Saunders, Historical evidence for energy efficiency rebound in 30 US sectors and a toolkit for rebound analysts, Technol. Forecast. Soc. Change. 80 (2013) 1317–1330, https://doi.org/10.1016/j.techfore.2012.12.007.
[40] C.M. Dufournaud, J.T. Quinn, J.J. Harrington, An applied general equilibrium (AGE) analysis of a policy designed to reduce the household consumption of wood in the Sudan, Resour. Energy Econ. 16 (1994) 67–90, https://doi.org/10.1016/0928-7655(94)90014-0.
[41] A. Kydes, Energy intensity and carbon emission responses to technological change: the US Outlook, Energy J. 20 (1999) 96–104, https://doi.org/10.5547/ISSN0195-6574-EJ-Vol20-No3-4.
[42] H.H.H. Semboja, The effects of an increase in energy efficiency on the Kenya economy, Energy Policy. 22 (1994) 217–225, https://doi.org/10.1016/0301-4215(94)90160-0.
[43] S. Glomsrød, W. Taoyuan, Coal cleaning: a viable strategy for reduced carbon emissions and improved environment in China? Energy Policy. 33 (2005) 525–542, https://doi.org/10.1016/j.enpol.2003.08.019.
[44] M. Howells, K. Jeong, L. Langlois, M.K. Lee, K.-Y. Nam, H.H. Rogner, Incorporating macroeconomic feedback into an energy systems model using an IO approach: evaluating the rebound effect in the Korean electricity system, Energy Policy. 38 (2010) 2700–2728, https://doi.org/10.1016/j.enpol.2008.10.054.
[45] P. Vikström, Energy efficiency and Energy Demand. A Historical CGE Investigation on the Rebound Effect in the Swedish Economy 1957, Swedish Institute for Growth Policy Studies, 2008.
[46] T. Washida, Economy-wide Model of Rebound Effect for Environmental Efficiency for the International Workshop on Driving Forces of and Barriers to Sustainable Consumption, in: Proc. Int. Workshop Driv. Forces Barriers Sutainable Consum., University of Leeds, Leeds, UK, 2004: pp. 292–301.
[47] G. Allan, N. Hanley, P. McGregor, K. Swales, K. Turner, The impact of increased efficiency in the industrial use of energy: a computable general equilibrium analysis for the United Kingdom, Energy Econ. 29 (2007) 779–798, https://doi.org/10.1016/j.eneco.2006.12.006.
[48] T. Broberg, C. Berg, E. Samakovlis, The economy-wide rebound effect from improved energy efficiency in Swedish industries–a general equilibrium analysis, Energy Policy. 83 (2015) 26–37, https://doi.org/10.1016/j.enpol.2015.03.026.
[49] N. Hanley, P.G. McGregor, J.K. Swales, K. Turner, Do increases in energy efficiency improve environmental quality and sustainability? Ecol. Econ. 68 (2009) 692–709, https://doi.org/10.1016/j.ecolecon.2008.06.004.
[50] K. Turner, N. Hanley, Energy efficiency, rebound effects and the environmental Kuznets Curve, Energy Econ. 33 (2011) 709–720, https://doi.org/10.1016/j.eneco.2010.12.002.
[51] G. Allan, M. Gilmartin, K. Turner, P. McGregor, K. Swales, UKERC Review of Evidence for the Rebound Effect, UK Energy Research Centre London, London, UK, 2007.
[52] J. Freire-González, Evidence of direct and indirect rebound effect in households in EU-27 countries, Energy Policy. 102 (2017) 270–276, https://doi.org/10.1016/j.enpol.2016.12.002.
[53] S. Koesler, K. Swales, K. Turner, International spillover and rebound effects from increased energy efficiency in Germany, Energy Econ. 54 (2016) 444–452, https://doi.org/10.1016/j.eneco.2015.12.011.
[54] T. Wei, Y. Liu, Estimation of global rebound effect caused by energy efficiency improvement, Energy Econ. 66 (2017) 27–34, https://doi.org/10.1016/j.eneco.2017.05.030.
[55] P. Brockway, H. Saunders, M. Heun, T. Foxon, J. Steinberger, J. Barrett, S. Sorrell, Energy rebound as a potential threat to a low-carbon future: findings from a new exergy-based national-level rebound approach, Energies. 10 (2017) 51, https://doi.org/10.3390/en10010051.
[56] B.K. Sovacool, J. Axsen, S. Sorrell, Promoting novelty, rigor, and style in energy social science: towards codes of practice for appropriate methods and research design, Energy Res. Soc. Sci. 45 (2018) 12–42, https://doi.org/10.1016/j.erss.2018.07.007.
[57] K.D. Bailey, Typologies and taxonomies: an introduction to classification techniques, Sage, Thousand Oaks, CA, USA, 1994.
[58] S. Kluge, Empirisch begründete Typenbildung in der qualitativen Sozialforschung, Forum Qual. Sozial. Qual. Soc. Res. 1 (2000) 11.

[59] D. Collier, J. LaPorte, J. Seawright, Typologies: Forming concepts and creating categorical variables, in: M. Janet, H.E. Brady, D. Collier (Eds.), Oxf, Oxford University Press, Oxford, Handb. Polit. Methodol., 2008, pp. 152–173.
[60] D. Collier, J. LaPorte, J. Seawright, Putting typologies to work: forming concepts and creating categorical measures, Polit. Res. Q. 65 (2012) 217–232, https://doi.org/10.1177/1065912912437162.
[61] A. Baker, Simplicity, Stanf. Encycl, Philos, 2016 https://plato.stanford.edu/archives/win2016/entries/simplicity/ (accessed May 1, 2020).
[62] J.C.J.M. van den Bergh, Energy conservation more effective with rebound policy, Environ. Resour. Econ. 48 (2011) 43–58, https://doi.org/10.1007/s10640-010-9396-z.
[63] S. Sorrell, Jevons' Paradox revisited: the evidence for backfire from improved energy efficiency, Energy Policy. 37 (2009) 1456–1469, https://doi.org/10.1016/j.enpol.2008.12.003.
[64] D. Maxwell, P. Owen, L. McAndrew, K. Muehmel, A. Neubauer, Addressing the Rebound Effect, European Commission DG ENV, Ivry-Sur-Seine, France, 2011.
[65] R.J. Michaels, Energy Efficiency and Climate Policy: The Rebound Dilemma, Institute for Energy Research (IER), 2012.
[66] J.M. Polimeni, K. Mayumi, M. Giampietro, B. Alcott (Eds.), The Jevons paradox and the myth of resource efficiency improvements, Earthscan, London, 2008.
[67] L. Schipper, M. Grubb, On the rebound? Feedback between energy intensities and energy uses in IEA countries, Energy Policy. 28 (2000) 367–388, https://doi.org/10.1016/S0301-4215(00)00018-5.
[68] S. Sorrell, Energy substitution technical change and rebound effects, Energies. 7 (2014) 2850–2873.
[69] ILO, IMF, OECD, Eurostat, UNECE, World Bank, Producer Price Index Manual: Theory and Practice, International Monetary Fund, Washington DC, USA, 2004. https://stats.oecd.org/glossary/detail.asp?ID=5691 (accessed May 19, 2020).
[70] P.A. Samuelson, W.D. Nordhaus, Economics, 19. ed, McGraw-Hill/Irwin, Boston, Mass., 2010.
[71] T. Friedrichsmeier, E. Matthies, Rebound effects in energy efficiency—an inefficient debate? GAIA-Ecol. Perspect. Sci. Soc. 24 (2015) 80–84.
[72] S. Borenstein, A microeconomic framework for evaluating energy efficiency rebound and some implications, National Bureau of Economic Research, Berkeley, CA, 2013.
[73] J.M. Keynes, General theory of employment, interest and money, Macmillan & Co., London, 1936.
[74] M. Wackernagel, W.E. Rees, Perceptual and structural barriers to investing in natural capital: economics from an ecological footprint perspective, Ecol. Econ. 20 (1997) 3–24, https://doi.org/10.1016/S0921-8009(96)00077-8.
[75] G. Colmenares, A. Löschel, R. Madlener, The Rebound Effect and its Representation in Energy and Climate Models, Institute for Future Energy Consumer Needs and Behavior (FCN), Münster, Germany, 2018.
[76] T. Santarius, H.J. Walnum, C. Aall (Eds.), Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon, Springer International Publishing, Switzerland, 2016.
[77] R. Galvin, A. Gubernat, The rebound effect and Schatzki's social theory: reassessing the socio-materiality of energy consumption via a German case study, Energy Res. Soc. Sci. 22 (2016) 183–193, https://doi.org/10.1016/j.erss.2016.08.024.
[78] B. Girod, P. De Haan, Mental Rebound, ETH Zurich, IED-NSSI, Zurich, Switzerland, 2009.
[79] F. Ruzzenenti, R. Basosi, The rebound effect: an evolutionary perspective, Ecol. Econ. 67 (2008) 526–537, https://doi.org/10.1016/j.ecolecon.2008.08.001.
[80] M. Sonnberger, M. Gross, Rebound effects in practice: an invitation to consider rebound from a practice theory perspective, Ecol. Econ. 154 (2018) 14–21, https://doi.org/10.1016/j.ecolecon.2018.07.013.
[81] S. Sorrell, B. Gatersleben, A. Druckman, The limits of energy sufficiency: a review of the evidence for rebound effects and negative spillovers from behavioural change, Energy Res. Soc. Sci. 64 (2020), 101439, https://doi.org/10.1016/j.erss.2020.101439.
[82] D. Font Vivanco, R. Kemp, E. van der Voet, How to deal with the rebound effect? A policy-oriented approach, Energy Policy. 94 (2016) 114–125, https://doi.org/10.1016/j.enpol.2016.03.054.
[83] S. Safarzadeh, M. Rasti-Barzoki, S.R. Hejazi, A review of optimal energy policy instruments on industrial energy efficiency programs, rebound effects, and government policies, Energy Policy. 139 (2020), 111342, https://doi.org/10.1016/j.enpol.2020.111342.
[84] L. Adua, B. Clark, R. York, The ineffectiveness of efficiency: the paradoxical effects of state policy on energy consumption in the United States, Energy Res. Soc. Sci. 71 (2021), 101806, https://doi.org/10.1016/j.erss.2020.101806.
[85] R. Galvin, Who co-opted our energy efficiency gains? A sociology of macro-level rebound effects and US car makers, Energy Policy. 142 (2020), 111548, https://doi.org/10.1016/j.enpol.2020.111548.
[86] J. Rosenow, F. Kern, K. Rogge, The need for comprehensive and well targeted instrument mixes to stimulate energy transitions: the case of energy efficiency policy, Energy Res. Soc. Sci. 33 (2017) 95–104, https://doi.org/10.1016/j.erss.2017.09.013.