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Economy-Wide Rebound Effects: State of the art, a new taxonomy, policy and research gaps

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Abstract

This is the first output for a 3-year research project (*ReCap*), which is focusing on economy-wide rebound effects and how to mitigate them through policy action. This discussion paper has been written collectively by the research team and has two aims: One is to develop a systematic understanding of the various kinds of rebound effects that are discussed in the literature. This provides to basis for our second aim, which is to analyse the state of research on rebound effects regarding the question of how rebounds can be limited through policy action. In this discussion paper, we therefore introduce a novel multi-level typology of rebound effects, which builds on and extends earlier typologies. In our taxonomy, we differentiate between various micro-, meso- and macroeconomic rebound effects, which arise at micro, meso and macro levels. In the following in-depth literature review, we consider both bottom-up and top-down approaches to studying rebound effects in theory and empirical research before turning to potential policies for mitigating rebound effects. We conclude with an overview of issues for future research and ways in which *ReCap* intends to contribute to their advancement.

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1. Introduction

Environmental issues become ever more urgent (Steffen et al., 2015). The global economy needs to be transformed in the coming decades in order to prevent more frequent and severe natural catastrophes due to continued climate change (Intergovernmental Panel on Climate Change, 2018). In order to mitigate climate change as much as possible, it is of vital importance to decrease greenhouse gas emissions from the energy sector, because burning fossil fuels accounts for 80% of such emissions (Pachauri et al., 2014). There are two major strategies to achieve emission reductions from energy consumption: (1) shifting from fossil fuel towards clean(er) energy forms and (2) reducing total energy consumption (Brockway et al., 2017).

One key approach to reducing total energy consumption is to increase energy efficiency. Holding output constant, increasing energy efficiency leads to lower energy consumption. However, over the last 35 years a large body of literature on rebound effects has emerged that questions the effectiveness of this strategy (Santarius, Walnum, & Aall, 2016b; Herring & Sorrell, 2009). Rebound effects describe how increases in energy efficiency change energy consumption – beyond their initial effect of decreasing it. Therefore, the economy-wide (or total) rebound effect is often defined as the difference between the reduction of energy consumption that would follow from the increase in efficiency ceteris paribus, and the actual change in energy consumption it causes. Over the last decades, a large body of literature on rebound effects has emerged. Many of such investigations are on the micro level and focus on households rather than firms. There is also some literature on rebound effects at the meso (sectors and markets) and the macro (national) level. The focus of the research on rebounds in general has been on explaining rebound effects and estimating their size. In contrast, despite the significance of rebound effects and their potentially negative effects on the outcomes of energy efficiency policy, there is only a limited number of articles specifically focusing on policies to mitigate rebound effects (see section 4 for details). We contribute to the literature by systematically distinguishing between rebound effects at different levels and by using this taxonomy to discuss policy measures to minimise rebound effects. We thereby strengthen the analytical foundations of policy measures and indicate possible areas of further research.

In this article, we analyze the state of research on rebound effects regarding the question of how rebounds can be limited through policy action. However, before one can tackle rebound effects, one needs to systematically understand them, which is the second aim of the article. In principle, there are two ways in which to understand economy-wide rebounds (Madlener & Alcott, 2009). The first is to capture a wide range of mechanisms stemming from increases in energy efficiency. While this bottom-up approach is always in danger of not covering all relevant mechanisms, it allows to indicate a variety of policy measures for limiting specific rebound mechanisms. The second approach is to assess the economy-wide rebound effect top-down on the macro level. Due to the macroeconomic nature of these analyses, the resulting policy recommendations are mostly stressing the importance of economy-wide carbon pricing/trading. The combination of insights from both approaches facilitates (1) an improved understanding of which rebound effects are at work, leading to the economy-wide rebound and (2) how they can be addressed by policy-makers. Regarding the size of the economy-wide rebound, this combination allows to capture a large list of rebounds and their concrete mechanisms. In terms of policies, it delivers not only a comprehensive list of policy-proposals but also a better understanding regarding which situation calls for which policy. In order to structure the rebound effects and the policies stemming from this analysis, we develop a taxonomy of rebound effects and match policy proposals to it. In the taxonomy, we differentiate between various micro-, meso- and macroeconomic *rebound effects*, which arise at micro, meso and macro *levels*. Additionally, we develop suggestions for further research and show how the project *Recap* helps to fill existing research gaps.

The remainder of the article follows four analytical steps. First, we give an overview of important rebound mechanisms from the bottom up and cluster them according to the level they refer to – micro-, meso-and macro. Second, we review literature on macroeconomic top down approaches to economy-wide rebounds. Third, we review suggested instruments by the policy-oriented literature on rebound mitigation. Fourth, we point out research gaps and outline ways in which the research project *ReCap* contributes to filling these gaps.

2. From the bottom up: Micro-, Meso-, Macro-economic Rebound Effects and Levels

The beginning of research on the rebound effect goes back to Jevons in 1865 (1906) who shows that a more economical use of coal would not reduce overall demand, but increase it in the long-run. More than one hundred years later, Khazzoom (1980, 1987, 1989) and Brookes (1990; 1978) developed similar lines of arguments regarding energy efficiency and energy consumption, which has therefore been termed the "Khazzoom-Brookes-Postulate": Increases in energy efficiency "would increase energy use relative to a zero value [the situation without the increase in energy efficiency]" (Saunders, 1992, p. 133, 2000a). Khazzoom focused on household appliances and thereby has developed the basis for research on microeconomic rebound effects. Brookes took a macroeconomic perspective and has laid the ground for current debates on economy-wide rebound effects. Since the 1980s, research on rebound effects has surged. In the 1990s, the basic concepts of Jevons, Khazzoom and Brookes have been substantiated and empirically tested (see Alcott (2005) for an overview). First meta-analyses of this research have been conducted in the late 1990s (Greening & Greene, 1998; Greening, Greene, & Difiglio, 2000). There is a vast number of microeconomic studies on the consumer-side (for an overview see Sorrell et al. (2009)), whereas micro-economic research on the producer-side is very limited (Turner, 2012). At the same time, rebound effects on the macro level have also been discussed, with early contributions by Brookes (2000) and Saunders (1992, 2000a).

In the following, we first review prominent taxonomies of rebound effects. Second, we argue why the taxonomy of micro-, meso- and macroeconomic effects is most suitable for our purposes and develop it further. The following three sections review micro-, meso- and macroeconomic rebound effects as described in the literature.

2.1 Existing taxonomies and lists of rebound effects

By now, there are several taxonomies of rebound effects. Following Turner (2012), we focus on four contributions by Greening et al. (2000), Sorrell (2007), Van den Bergh (2011) and Madlener and Alcott (2009). We complement these taxonomies with later contributions, which have extended them and provide our own taxonomy which draws on Santarius (2016b).

In an early contribution, Greening et al. (2000) distinguish four types 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 refer to the increased use of the energy service where the increase in efficiency takes place. Secondary fuel use effects are what is often called indirect effects today, 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) and thereby influence the price of energy services and of energy supply and even technological change. Transformational effects in addition “change consumers’ preferences, alter social institutions and rearrange the organization of production” (p. 391). Greening et al. therefore propose a taxonomy that includes both short and long-term effects regarding all kinds of aspects such as actors, institutions, norms etc.

Sorrell (2007) put forward three categories: (1) direct, (2) indirect and the (3) economy-wide effect. Direct effects again refer to the increase of the good or service which experiences the increase in efficiency. Sorrell further distinguishes between direct effects for households and firms. Each set of actors experiences a substitution and an income/output effect. Households substitute the now cheaper good or service for other goods or services and additionally experience an increase in income, leading to overall higher consumption of the good or service. Firms substitute the now cheaper energy service for other production factors (capital and labour) and additionally increase production based on the good or service as an input. Indirect effects encompass a large range of effects in Sorrell’s taxonomy: additional consumption of other goods and services, the energy used for the technology that facilitates the increase in energy efficiency (also called embodied energy effect), a sector-wide decrease in the price of the good or service and hence an increase in its production and consumption, a decrease in overall energy price and consequently an increase in energy consumption as well as overall increases in productivity and thereby a positive effect on economic growth. In contrast to the taxonomy by Greening et al., the economy-wide effect is the sum of all direct and indirect effects.

In an *Energy Policy* special issue on the rebound effect, Schipper and Grubb were among the first to systematically distinguish between micro- and macroeconomic rebound effects (Schipper & Grubb, 2000). Since then, various authors have picked up this differentiation. Madlener & Alcott (2009) point out that, while microeconomic analyses in particular on the level of households are methodologically feasible, this becomes increasingly difficult with the level of aggregation. The reasons are that on the one hand, it is difficult to keep track of the multiple mechanisms following from increases in energy efficiency at the micro level (as is also apparent in the lists above). At the same time, it is methodically difficult to differentiate the effects of changes in energy efficiency on energy consumption from other effects on the macro level. Santarius (2016b) proposes to further include a meso level into the analyses, which encompasses rebound effects on the sectoral level. Madlener & Turner (2016) argue that four levels of aggregation can be differentiated: The household and firm level, the sectoral level, the economy-wide level and the international/global level. As the aim of this article is to understand economy-wide rebound effects on a national level, we follow Santarius in separating between micro, meso- and macroeconomic rebound effects. However, while Santarius is ambivalent whether to attribute the firm level to the micro-or the meso level, we attribute it to the micro one (see below). Regarding the international level suggested by Madlener and Turner, we only take into account effects that influence the rebound within one country (instead of analyzing rebound effects for the entire world).

Finally, Santarius, Walnum & Aall together with a growing number of other authors have begun to expand research on the rebound effect to other disciplines beyond economics (Santarius, 2016b). Greening et al. (2000) have already defined “transformational effects” (see above), but it is only in this decade that research has systematically begun to explain and define rebound effects from psychology, sociology, physics and urban planning perspectives (see Santarius et al., 2018a). The general argument behind such multi-disciplinary approaches is that (technical) efficiency improvements may not only affect prices, income, factor productivity or other economic categories, but also consumer preferences, social norms as well as other psychological, social, political or even cultural categories. Multi-disciplinary rebound research offers a new set of rebound effects and may inspire much expanded rebound taxonomies, including motivational effects, structural (sociological) effects, systems theory effects and more. Such research is most advanced in behavioral science (Girod & De Haan, 2009; Otto et al., 2014; Peters et al., 2012; Santarius, 2012; Suffolk & Poortinga, 2016), with Santarius and Soland (2018) suggesting a taxonomy of psychological rebound effects consisting of three rebound and two beneficial effects. This discussion paper focusses on rebound effects within economics literature, to limit the amount of literature and effects that needs to be taken into account. However, we note that first attempts have been made to analyze macro level effects from a sociological perspective by describing the relationship between energy efficiency improvements and the speed of consumption and production processes, product cycles, and the turnover and velocity of money (Santarius, 2016a). Taking such effects into account would be a fruitful endeavor for future research projects and may also improve policy recommendations.

2.2 Micro, Meso and Macro levels: Towards a typology of rebound effects

In order to be able to limit rebound effects, it is necessary to understand the various mechanisms via which increases in energy efficiency work their way through the economy. Only in this manner, it becomes possible to understand how to tackle them, be it via different behavior of individuals or firms, or via economic policies. The varying taxonomies and lists of rebounds described above serve exactly this purpose – to get an overview and cluster the various mechanisms.

We follow the logic of clustering the effects into micro-, meso- and macroeconomic rebound effects and use the categorizations of other taxonomies and their lists of rebound effects to develop our taxonomy (this is done in sections 2.12.2 - 2.5). In doing so, we make an important distinction between rebound effects and levels (see Figure 1). Levels refer to the level of economic aggregation, for which one wants to investigate the rebound effect. The micro level refers to the rebound effect for single firms or households, the meso level to a single sector and macro to a national economy. Rebound effects refer to mechanisms taking place at any of these levels. The differentiation is important because rebound effects at higher levels do not arise exclusively due to rebound effects at this level, but are triggered by effects at lower levels. In other words: The total rebound effect at a specific level is not only due to the rebound effects at that level but also due to the effects at lower levels (see 2.4 The meso level for details). For example, at the meso level, not only effects specific to the sector level need to be taken into account, but also the activities of households and firms. Energy efficiency in the production of cars allows car-producing companies to increase profits and expand production (a microeconomic rebound effect). However, when many firms introduce this new technology, price competition may lead to lower prices and thereby to higher sales (a mesoeconomic rebound effect). Accordingly, the economy-wide rebound at the macro level depends not only on macroeconomic rebounds but also on micro- and mesoeconomic ones. In the example of more efficient car-production, the more energy efficient production may lead to a significant decrease in energy demand and subsequently to a lower energy price – triggering rebounds in other sectors of the economy.

Figure 1 shows our taxonomy with the various rebound effects categorized into the different levels. The size of the rebound effect can be investigated at different levels: at the micro level it refers to the size of rebounds for single households or firms; at the meso level to single sectors or markets, at the macro level to single countries. At each of these levels, several distinct rebound effects can take place. The "total" rebound at a specific level is due to the combination of effects at that level and the lower levels. In terms of microeconomic rebound effects, firms and households use savings to re-spend or re-invest. In final and intermediate markets, lower prices lead to higher sales. In terms of mesoeconomic rebound effects, in single energy markets, lower prices lead to increasing usage of the respective energy carrier. At the macro level, decreases in energy price lead to more energy consumption; larger consumption and investments trigger larger income and demand by other actors;

changes in energy efficiency change global competitiveness and thereby lead to relocation of production; international energy markets influence the market price effect.

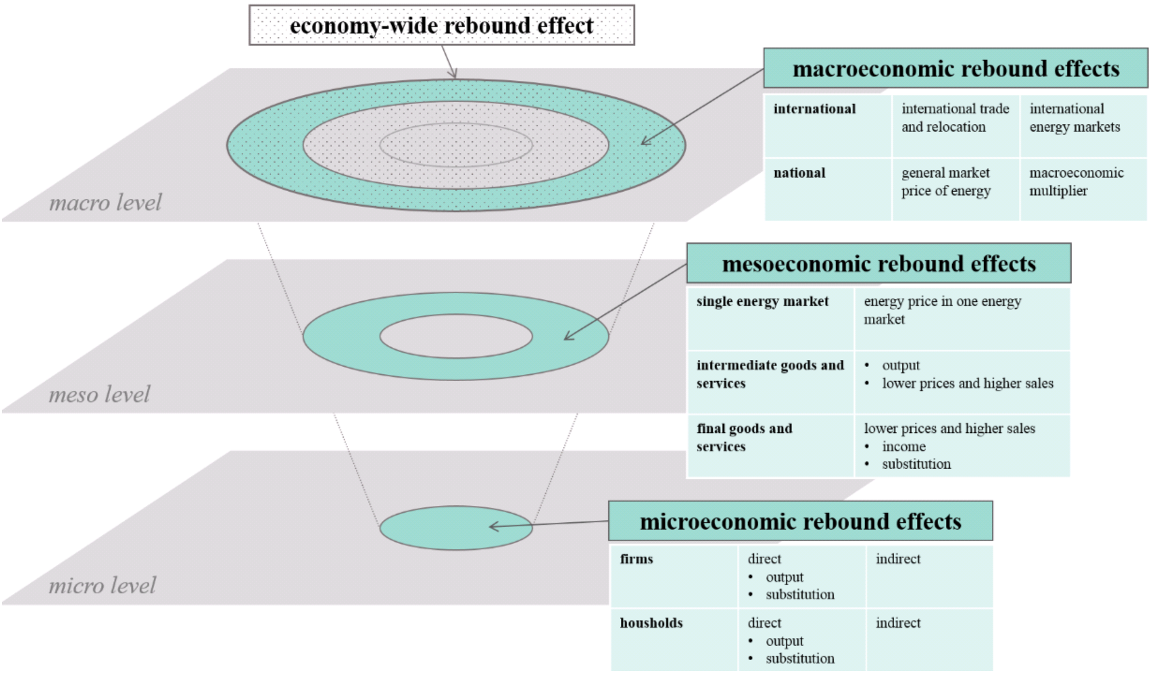

Figure 1: Micro-, meso and macroeconomic rebound effects

As the number of rebound effects rises with the level of aggregation, the rebound effect is expected to be higher for higher levels of aggregation: “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 & Keppler, 2000a, p. 463). However, this does not always have to be the case. As Koesler et al. (2016) show, energy efficiency gains in one firm can increase its market share and consequently its production – but at the same time lower the market share of another firm and its production.

To cluster rebounds according to the level of economic aggregation has two advantages, as compared to other typologies outlined above. First, it helps to prevent double-counting. Similar rebound effects, that take place at different levels, overlap. These must not be seen as separate mechanisms that can be added up. Rather, mechanisms start at the micro level and they trigger additional mechanisms at the meso and macro levels. The taxonomy of different levels helps to prevent analyses from regarding them as separate mechanisms. To give two examples: (1) One rebound effect results from the fact that producers use increases in energy efficiency to increase output, among others by investing into new capital stock (micro level). Another rebound effect describes how higher energy efficiency may lead to increases in overall productivity. However, the former is clearly part of the latter: The increases in overall productivity are partly due to the firms’ implementation of new technology with higher energy efficiency (see for example Sorrell (2007)). (2) Households substitute consumption so that they consume more of the good or service that has experienced the increase in energy efficiency and less of another. Also, firms are assumed to substitute energy for other production factors if energy efficiency increases. At the same time, at the macro level, one of the main determinants of the size of rebound is said to be the elasticity of substitution between energy and other production factors. Clearly, the two former mechanisms are part of the latter: The reaction of households and firms to increases in energy efficiency is an important determinant of the elasticity of substitution.

The second advantage refers to the aim of this article to develop more advanced policy thinking about how to limit rebound effects. In order to make concrete proposals how rebounds can be mitigated, it is necessary to point out the actors, who have to be addressed by policy to bring about this change. The clustering into micro-, meso- and macroeconomic effects corresponds to this goal as it shows which actors and mechanisms generate rebound effects and therefore allows more targeted thinking about what kind of policies are needed to make climate and energy policy as ‘rebound-proof’ as possible.

It is important to note that different authors often use the same term for different aspects within the rebounds literature. For example, mesoeconomic effects can include the firm-level (Santarius, 2016b) or refer to the sector-level only. Macroeconomic effects can refer to all but the direct effects, the sum of all effects in an economy (Madlener & Turner, 2016) or to original mechanisms taking place at the macro level (Barker et al., 2009) in particular the macroeconomic price and the macroeconomic growth effect (Gillingham et al., 2016). Similarly, economy-wide effects can denote all effects that are neither direct nor indirect (Barker et al., 2009) or be the sum of all effects (Madlener & Turner, 2016; Steve Sorrell, 2007). In Table 1, we specify the definitions used in this article.

Table 1: Definition of Rebounds

Microeconomic rebound effects	Rebound effects taking place at the level of individuals/households and firms.
Mesoeconomic rebound effects	Rebound effects taking place at the level of single markets or sectors
Macroeconomic rebound effects	Rebound effects taking place above the level of a single sector, at either the intersectoral, the national or the international level.
Economy-wide rebound effect	The total of all rebound effects within an economy caused by a specific set of increases in energy efficiency.
Direct rebound effects	Rebound effects changing the level of production and/or consumption of the good or service for which the increase in energy efficiency has taken place.
Indirect rebound effects	Rebound effects changing the production and/or consumption of other goods or services than the one for which the increase in energy efficiency has taken place.

The following three sections review micro-, meso- and macroeconomic rebound effects as described in the existing literature, which provide the basis for the topology developed above in terms of the levels and mechanisms.

2.3 The micro level

Microeconomic rebound effects encompass effects on the individual and on the firm level. The vast majority of literature is on households while research regarding firms is still scarce. The following differentiation between households and firms, between direct and indirect effects and between substitution and income/output effects is based on the taxonomy by Sorrell (2007) that has already been outlined above.

Microeconomic effects on the **individual** level are divided into direct and indirect effects. **Direct** effects refer to the change in energy consumption regarding the good or service, which experienced an increase in energy efficiency. For example, buying a more fuel efficient car can lead to an increase in kilometers driven. The indirect effect refers to the consumption of other goods or services. In this example, individuals could decide to use (part of) the money they saved on their car travel to spend the money on a short-haul flight for the weekend. The direct and indirect rebounds are due to two different effects - the income and substitution effects. Both effects can affect both kinds of rebounds. The **income** effect on the consumer side arises from the increase in real income resulting from the money savings generated by the more efficient car, which induces individuals to drive more or consume more of another good or service. The **substitution** effect implies for example that consumers decide to drive more and consume something else less, because driving has become relatively cheaper (for example, they use the car more and travel less by train).

By now, there is a large number of investigations of direct rebound effects at the individual level for various goods and services. Several meta-analyses have compared and synthesized these findings (Azevedo et al., 2012; Greening et al., 2000; Jenkins et al., 2011; Madlener & Alcott, 2011; Maxwell et al., 2011; Sorrell, 2007). Central insights are that the size of direct rebounds differs significantly between goods/services and sectors and that on average, direct rebounds are found to be between 10-30% , which means that the actual reduction in energy use is 10 – 30 % less than the technologically feasible efficiency gains would suggest (Santarius et al., 2016a; Steve Sorrell et al., 2009).

Compared to direct rebounds, there are only few articles on **indirect** rebound effects (Santarius, 2016a). The size of indirect rebounds depends on where the efficiency gains take place. Druckman et al. (2011) estimate indirect rebounds for three energy saving practices by households. They find that rebounds are lowest for reduced household energy use (7%), medium for lowering travel by walking more (25%) and highest for cutting food waste (51%). Chitnis et al. (2014) find that indirect effects are relatively small for domestic energy use (0–32%), bigger for vehicle use (25–65%) and even larger for measures that decrease food waste (66–106%). Thomas & Azevedo (2013) estimate both direct and indirect rebound effects from households' investments in energy efficiency. They find 5-15% direct and 30-40% indirect rebound effects.

As a significant share of energy is used on the production side, energy efficiency and rebounds in **firms** are of major importance. The fact that rebounds take place not only for consumers but also on the production side has already been part of the discussion since Jevons' contribution in the 19th century. In modern debates, Saunders (1992) was early in pointing this out. Rebound effects at the firm level were first discussed in detail by several papers in a special issue of the journal *Energy Policy* (Berkhout, Muskens, & Velthuijsen, 2000; Birol & Keppler, 2000a; Greening, Greene, & Difiglio, 2000). More recent contributions have been made by Michaels (2012), Saunders (2008), Sorrell (2007), Sorrell et al. (2009) and Turner (2012). On the firm level, two rebound mechanisms are theorized. (1) Firms use the monetary surplus available due to increases in energy efficiency of their production methods to expand their production level (Berkhout et al., 2000). Sorrell (2007) calls this the **direct effect** for firms. He argues that it entails an **output effect** due to the ability to produce more at the same costs and a **substitution effect**, as firms decide to use more energy services rather than other production factors (this point was earlier made by Berkhout et al., 2000 and Birol & Keppler, 2000a). Santarius (2016b) differentiates the output effect in expansion of production of the same good or service and expansion of production of other goods or services, terming the latter **indirect** effect in relations to firms. As Turner (2012) has pointed out, the issue of rebounds on the supply side has received little attention since.

The empirical literature on rebounds of firms is very limited. There are some investigations on the relationship between energy efficiency increases, output increases and energy consumption on the production side. For example Worrell et al. (2003) find that increases in energy efficiency go along with net increases in overall productivity. Dahmus and Gutowski (2014) show that the increases in output have outpaced the increases in energy efficiency for several economic activities. Nadel (1993) estimates a rebound effect of about 2% for process fuels in industrial facilities and 30% or more for lighting programs in buildings. However, to the best of our knowledge, there are no empirical investigations on the rebound effect for the producer side on the firm level, that attempt to establish a causal relation between the increase in energy efficiency and the change in energy consumption (which has been the topic of many studies for the consumer side). At the same time, there are several empirical investigations for the producer side on a sectoral level, which we turn to now.

2.4 The meso level

The next level of aggregation of rebounds is the mesoeconomic level, referring to single markets or sectors. The rebound within a sector can be explained by combining respective microeconomic rebounds for firms who produce within the sector and households who consume goods and services of the sector on the one hand, and additional rebound effects taking place at the mesoeconomic level. The latter are described in the following. The literature exhibits three different areas, where mesoeconomic rebounds take place: (1) In sectors for final goods and services, (2) in sectors for intermediate goods and services and (3) in single energy markets.

In final goods sectors, the mesoeconomic rebound effect starts from the same origin as microeconomic rebounds on the firm level. Firms lower their (energy-)costs by increasing energy efficiency. In the case of the microeconomic rebound, they use the savings to expand production. However, an alternative or additional effect is to use lower costs to offer goods and services at lower prices. Assuming a competitive market, if many firms follow this strategy, the market price of a good or service falls, which increases the amount of sales of this good or service and thereby for the entire sector (Birol & Keppler, 2000a). This effect also has an income effect and a substitution effect: The income effect describes that due to lower prices, consumers can afford more goods and services. The substitution effect is that consumers consume more of the good or service whose price has fallen, and less of other goods and services (compare Jenkins et al. (2011), Santarius (2016b) and Turner et al. (2009)).This effect can be strengthened further when the increase in energy efficiency leads to a shift of investments into that sector. As this (still relatively energy intensive) sector grows in relation to other sectors, total energy consumption also increases (Gillingham et al., 2016).

Second, increases in energy efficiency in the production of intermediate goods or services can lead to lower prices of such goods or services and thereby to lower costs for the firms using the intermediate goods or services in their production. This may lead to one or both of the following rebound effects. The firms can use the lower costs to increase production (Santarius, 2016b) or, when it concerns many firms in a market or sector, they may decrease the price of the final good, leading to higher consumption and an expansion of production.

Third, mesoeconomic rebound effects can take place in a single energy market of a specific energy carrier, induced by higher energy efficiency for the firms and households using this energy carrier. As discussed in more detail below, effects on the overall energy market as a whole are considered a macroeconomic rebound effect. A general increase in energy efficiency can decrease the average energy price and, as almost all goods and services need some input of energy, have a macroeconomic rebound effect. However, there is more than one energy market. There are markets for oil, petrol, gas, coal, lignite, electricity, etc. Whenever a significant number of firms using one of such energy inputs increases its energy efficiency, the demand for this type of energy decreases. Depending on the elasticity of supply of this type of energy, the price will decrease (Borenstein, 2013). As a response, the use of this type of energy will be larger than what we would expect from the energy efficiency increases alone.

There are several empirical investigations regarding rebound effects in final goods sectors – far less than for microeconomic effects on the consumer side but more than for microeconomic effects on the producer side. There are several studies regarding single sectors. Lin and Li (2014) estimate an energy rebound effect of 74.3% percent for heavy industry in China. Bentzen (2004) finds a 24% rebound effect for the US manufacturing sector. Orea et al. (2015) investigate the US residential sector and find a rebound effect between 56-80%. Several studies have investigated freight and air transportation, finding rebounds between 17% and 80% (Anson & Turner, 2009; De Borger & Mulalic, 2012; Gately, 1990; Graham & Glaister, 2002; Wang & Lu, 2014). Two studies have investigated several sectors at the same time, also including energy sectors. Grepperud and Rasmussen (2004) investigated a wide range of sectors in Norway and found very heterogeneous sizes of rebound effects between the sectors: In one (manufacture of metals) out of six investigated sectors, a strong rebound effect could be identified. They find that rebound effects are larger in energy-intensive sectors than in sectors with low energy-intensity. Additionally, they argue that the substitution possibilities between energy sources/sectors are relevant to determine the size of the rebound effect in the final good sector. For instance, in the metal sectors the rebound effects tend to be high because of low substitution possibilities between oil and electricity. Saunders (2013) comes to similar results. He examines 30 sectors in the US economy. He finds very different sizes in different sectors and that in energy-intensive sectors such as in transportation or manufacturing the rebound effects are higher. Zhang (2017) compares the rebound effect of different Chinese industrial sectors with a panel data approach and finds a rebound effect of 39% on average between 1995-2002.

2.5 The macro level

The macro level refers to the total rebound at the national level, which is the economy-wide rebound effect. It is explained by the combination of micro- and mesoeconomic rebound effects described in 2.3 and 2.4 and additional effects taking place in the economy of an entire country (national) and between countries (international). We use the term “macroeconomic rebound effects” for such national and international mechanisms. The international mechanisms taken into account are limited to such mechanisms that (a) originate in the country under investigation and (b) have an effect within the country under investigation. We therefore exclude mechanisms originating in other countries or effects on other countries. The reason is that the taxonomy developed is designed to understand the determinants of the economy-wide rebound for one country that is due to an energy efficiency increase within that country. The term “macroeconomic rebound effect” is clearly demarcated from the “economy-wide rebound effect”, which is the total rebound in an economy and therefore includes micro-, meso- and macroeconomic rebound effects. The literature specifically focusing on such macroeconomic rebound effects is rather limited. Gillingham et al. (2016) differentiates between a macroeconomic price effect and several macroeconomic growth effects. However, many of the growth effects listed by these authors are microeconomic rebound effects in our categorization. For example, both include the effects of additional spending of consumer and additional investments by firm as macroeconomic effects. While we agree that both contribute to GDP growth, they are microeconomic effects. We focus on additional effects not already covered by microeconomic effects and cluster them in effects taking place in one economy (national) and those including mechanisms between different economies (international).

At the national level, there are three central effects. The macroeconomic **price effect** is similar to the mesoeconomic effect in energy markets. If energy efficiency increases for many actors (on the producer and/or consumer side), overall demand for energy decreases. Depending on the elasticity of energy supply, this leads to a lower price for energy and a larger use of it. At the macro level, the price effect relates to several or all sources of energy. If the price of one energy carrier changes, this can also influence the price of other energy carriers if they are substitutable. Another case is where technological change does not only increase the energy efficiency in one but several energy carriers. In both instances, actors experience lower energy prices and therefore have an incentive to use more energy. Second, there is a **macroeconomic multiplier** of energy efficiency increases. The actors who experience an improvement in energy efficiency save money and spend it on additional goods and services (this is the sum of microeconomic effects). This increases income of the producers (employers and employees) of these additional goods and services. They in turn spend this income on additional goods throughout the economy (Borenstein, 2013; Gillingham et al., 2016). This macroeconomic multiplier follows the same logic of the traditional multiplier-effect, which has been prominently argued for by Keynes (2006) and is part of most macroeconomic textbooks. At the same time it is argued that the macroeconomic rebound multiplier is different to the traditional multiplier effect, because the additional money for demand does not stem from additional government debt or increases in taxes (Borenstein, 2013; Gillingham et al., 2016). Third, increases in energy efficiency may lead to increases in **total factor productivity**, which in turn increases total production and hence the energy consumption (van den Bergh, 2011).

At the international level, two effects are discussed in the literature. First, **international trade and relocation** can be affected (van den Bergh, 2011). If increases in energy efficiency take place only in firms in one country or a set of countries, this improves the competitiveness of such firms compared to firms in other countries. As a result, the production of such firms increases, while that of firms in other regions may decrease. From a national perspective, the rebounds may therefore appear to be larger than from a global perspective. Second, many **energy markets** (such as the oil market) are international, rather than national. Therefore, changes in the energy efficiency in the rest of the world can influence energy prices and thereby lead to rebounds in countries, without them experiencing higher energy efficiency themselves.

2.6 Summary

The analysis of micro-, meso and macroeconomic rebound effects has shown that the growing literature on rebounds has identified a large number of different mechanisms though which increases in energy efficiency impact upon the level of energy consumption. The mechanisms discussed here cover the most important mechanisms discussed in the literature. Nevertheless, they do not cover all relevant mechanisms. In particular, non-economic rebound effects, such as psychological, sociological, etc., have not been included in the analysis. Nevertheless, more generally speaking, it is analytically impossible to cover all mechanisms stemming from increases in energy efficiency and having an impact on energy consumption. Therefore, another fruitful and complementary approach is to analyze the economy-wide rebound effect from the top-down, by looking at aggregated variables. This is the topic of the next section.

3. From the top down: Economy-wide rebound effects

In section 2, we have taken a bottom-up approach to understanding economy-wide rebound effects. We listed various single rebound effects and clustered them into micro-, meso- and macroeconomic rebounds. The idea was that by understanding many different rebound effects, it becomes possible to capture as much as possible of the determinants of the economy-wide rebound. However, the described rebounds on the micro, meso and macro level are most probably not comprehensive. Due to the countless causes and effects in an economy, it is not possible to encompass all effects, let alone to attribute how much each rebound effect contributes to the economy-wide rebound effect: “the global economy is a single, interconnected, complex dynamic system, making definitive arguments about cause and effect nearly impossible” (Gillingham et al., 2016). Another complementary approach is therefore to explain the economy-wide rebound effect based on aggregated (macroeconomic) factors.

In this section we therefore take a different approach to understanding the economy-wide rebound. Here, we analyze contributions that take a top-down approach. These use one method to capture the total/economy-wide rebound, rather than identifying and measuring many single rebounds. Madlener and Turner (2016) differentiate between ex-ante and ex-post studies regarding economy-wide rebounds. Additionally, there are theoretical contributions on the macro level, mostly using economic growth theories. We therefore cover three different types of top-down approaches to investigate economy-wide rebounds. First, they can be explained theoretically using macroeconomic theories.

Second, empirical ex-post approaches investigate the size of past economy-wide rebounds. Third, empirical and theoretical work can be combined in macroeconomic models to anticipate future rebound effects, in so-called ex-ante approaches.

3.1 Theoretical macroeconomic approaches

One way to explain economy-wide rebounds is to use macroeconomic theories. With the use of such theories one can investigate the effects of increases in energy efficiency on energy consumption on the macroeconomic level and thereby directly examine the determinants of economy-wide rebounds. Such research differs from the research covered in section 2.5. The macroeconomic rebound effects discussed in section 2.5 are specific rebound effects taking place at the national and international levels. They are complementary to microeconomic and mesoeconomic rebound effects. The macroeconomic theories covered in this section on the contrary, solely deal with aggregated variables such as total factor supplies, aggregate supply of goods and services, aggregate demand of goods and services, etc. The theories therefore encompass the effects at the micro, meso and macro levels – not by indicating all the single effects but by dealing with the aggregated variables. Following Sorrell and Dimitropoulos (2007), the literature can be differentiated into (1) the early contributions by Brookes, (2) the application of neoclassical growth theories by Saunders and (3) approaches from ecological economics.

(1) Brookes (1990; 1978; 2000) was the first (after the early contributions of Jevons in the 19th century) to argue on the macroeconomic level that increases in energy efficiency would lead to significant economy-wide rebound effects. In fact, he proposed that energy consumption would increase due to improvements in energy efficiency, so called backfire. His core argument is that increases in energy efficiency go along with economic growth, which in turn increases the demand for energy and therefore also energy consumption. Particular importance is attributed to the productivities of the other production factors: Increases in energy efficiency are associated with increases in the productivity of capital and labour (combined often called total factor productivity). Such higher total factor productivity leads to an expansion of production, which in turn increases the demand for energy. Brookes argues that this (positive) additional demand for energy more than outweighs the (negative) effect of energy efficiency on energy consumption – leading to backfire. He also refers to empirical support of his claim. Sorrell and Dimitropoulos (2007) point out several weaknesses in his argument and the empirical support for backfire. However, the discussion whether the economy-wide rebound is smaller or larger than 100% is not the focus of the present study and the core argument that energy efficiency leads to additional economic growth and thereby to more energy demand seems to be undisputed.

(2) Saunders (1992, 2000a, 2008), explicitly relating to Brookes' work, has applied neoclassical growth models to the question of the size of the economy-wide rebound, in particular whether such theories predict backfire. In an early contribution (Saunders, 1992), he used standard neoclassical production functions (Cobb-Douglas and nested Constant Elasticity of Substitution functions) to investigate the effect of different types of technological change (neutral, capital-augmenting, labour-augmenting and energy-augmenting) on energy consumption. Almost all parameter specifications led to backfire. Only the nested CES function predicted no backfire in the case of energy-augmenting technological change and low substitutability between energy and other production factors. Howarth (1997) critized Saunders' analysis, arguing that one needs to take into account that the supply of energy services also requires capital and labour. However, Saunders (2000b) showed that Howarth's critique depends on the specific
(Leontief) production function Howarth chose for the supply of energy services. In later work, Saunders has investigated which type of production functions do and which don't predict backfire (Saunders, 2008). His work shows that, while the most widely used production functions predict backfire, the size of the economy-wide rebound depends heavily on the function used and parameters assumed. Sorrell and Dimitropoulos (2007) argue that the prediction of backfire in the prominent functions can either be interpreted as a high probability for backfire, or that such functions do not appropriately represent the empirical reality of the economy-wide rebound effect.

(3) Saunders' investigations are explicitly based on neoclassical theories regarding the relation between energy and growth. Ecological economics approaches this relationship in a very different way. While such theories have not been explicitly applied to the economy-wide rebound effect, they implicitly contribute a very different perspective to it (Steve Sorrell & Dimitropoulos, 2007). The central difference between neoclassical and ecological economics is the role they attribute to energy for economic growth. In neoclassical theories, the level of output typically determines the demand for energy and therefore the level of energy consumption. This is why Saunders finds (using neoclassical theories) that more energy efficient technologies can lead to more energy consumption via increased production. Ecological economists on the other hand regard the supply of energy as an important determinant of economic activity. That is why reducing energy supply (for environmental reasons) would decrease economic output (while neoclassical economists argue that this could be compensated by substituting energy by other production factors). What does this imply for the size of economy-wide rebounds? As Sorrell argues, increases in energy efficiency lead to larger impacts on economic growth in the theories of ecological economics than in neoclassical theories. The higher level of output in turn spurs up demand for energy – and therefore lead to a large economy-wide rebound.

Two further important determinants of the economy-wide rebound arise from these macroeconomic theories. First, approaches from ecological economics place an emphasis on the energy embodied in new technology. The production of new technology needs energy and materials (Ayres & Warr, 2010). Second, the elasticity of supply of energy is crucial. If increases in energy efficiency lead to economic growth, which in turn increases the demand for energy and potentially leads to backfire, the elasticity of energy supply determines whether this goes along with a change in the energy price – which in turn influences the size of energy consumption.

It appears that, both in neoclassical theories, as well as ecological economics approaches, the economy-wide rebound is expected to be large under usual assumptions – often even backfire is predicted. Central determinants of the size of the rebound are (1) the role of energy for economic growth (the output-elasticity of energy and the additional energy demand due to increases in output), (2) the elasticity of supply of energy and (3) the embodied energy in new technology.

At the same time, the contributions are limited to a few authors. While traditional neoclassical approaches have been examined by Saunders, newer approaches such as directed technical change, are barely investigated (with a mentionable exception by Hart (2018). Approaches from the second important strand on the relationship between economic growth and energy – ecological economics – have barely been applied to the issue of economy-wide rebound. A fruitful area for future research is therefore to investigate economy-wide rebounds by the use of a wider range of macroeconomic theories (see section Macroeconomic theories**)**.

3.2 Empirical ex-ante models

There are various studies which investigate economy-wide rebound effects by using empirically-based macroeconomic models. Such models are "ex-ante", as they anticipate the rebound effects of potential changes in energy efficiency based on existing models of the economy. These make use of macroeconomic (growth) models, Computable General Equilibrium (CGE), and macroeconometric models, the last two including the industry structure of the economy based on input-output (I-O) tables. Macroeconomic models explain the combination of production factors labor, capital, material, and (sometimes) energy and the contribution of technical progress for the increase in production. The two other models depict the change in industry structures due to policy measures such as tax changes, changes in important macroeconomic factors such as energy prices, or – in the case of rebounds – an energy efficiency increase. CGE models are supply-side driven, build on neoclassical theory of optimisation and market clearance. Macroeconometric models emphasize empirical relations and take the demand side more into account. Both types of models are used frequently to study policy impacts.

Early anlyses were conducted in the 1990s on the US (Kydes, 1999), Sudan (Dufournaud, Quinn, & Harrington, 1994) and Kenya (Semboja, 1994). In more recent years, the literature has expanded. By now there exist case studies of different types for environmental policies in Japan (Washida, 2004), efficient coal technologies in China (Glomsrød & Taoyuan, 2005), energy efficiency policies in the UK (Barker & Foxon, 2006), energy efficiency improvements in Sweden (Vikström, 2008) and replacing coal by nuclear energy in Korea (Howells et al., 2010). Additionally, there has been a series of investigations on a exogenous 5% increase in energy efficiency throughout the economy or only in industry (Grant Allan et al., 2007; Broberg et al., 2015; Hanley et al., 2009; Turner & Hanley, 2011). Other approaches have tackled the issue of rebound effects on a global scale (Barker et al., 2009; Wei, 2010).

Allan et al. (2007) compare results of 8 CGE modelling studies, including the above cited studies on Sudan, Kenya, Sweden, Norway, China and the UK. The minimum economy-wide rebound found in the CGE studies is 37% and most studies show either large rebounds (>50%) or backfire (for two studies of open economies where energy is an important export commodity)

Most of these empirical approaches assume an autonomous increase of energy efficiency and analyse rebound effects at the macro and meso levels in comparison to a baseline without the efficiency improvement (Table 1). Banning and Lutz (2019) have analysed examples for the three important approaches in detail to understand how rebound effects have been calculated and what has been identified as most important driving factors: Saunders (2000a) as a macroeconomic model, Barker & Foxon (2006) as a national macroeconometric model, Allan et al. (2007) as a CGE model with focus on the UK, and Koesler et al. (2016) as a global CGE model.

The studies of Allan et al. (2007), Barker et al. (2009) and Koesler et al. (2016) capture mesoeconomic and macroeconomic effects. The models applied in these studies separate different homogenous industries. Their production depends on prices of production factors and demand, which in turn is a function of the different goods produced by these industries. All the mesoeconomic and the macroeconomic rebound effects – on national or national and international level – described in Figure

1 take place simultaneously. They report macro rebounds between 11% and 62% according to their modelling approach including model type, analysed region and elasticities of substitution (for fuels and non-fuels at sector/meso level) determine the results. Elasticities of substitution describe how households will change their demand or industries their mix of intermediate inputs, if relative prices (of energy in relation to other goods) change. The relation between capital and energy is debated. It may depend on the sector or even on the product, whether, and to which extent, they are complementary or substitutes. Broadstock et al. (2007) conclude: „If a general conclusion can be drawn, it is that energy and capital typically appear to be either complements (AES<0) or weak substitutes (0<AES<0.5)". But they have "little confidence in this conclusion, given the diversity of the results and their apparent dependence upon the particular specification and assumptions used." Rebound definition, time horizon and country specific structures. i.e. production, consumption, energy use and trade data, also influence the magnitude of the effects. Koesler et al. (2016) include international effects, i.e. what happens in other countries, while the other two stop their analysis at the export and import volumes and prices of the examined country. Saunders (2000a) shows at the macro level, that neoclassical growth models can deliver very different insights, including the explanation of backfire. His analysis remains at the macroeconomic level. He pronounces the highly empirical nature of the rebound effect, as the magnitude of rebound effects depends on sets of parameter assumptions. This means that he can produce a broad range of rebound effects in his model with different plausible sets of parameters, which highlights the importance of robust empirical ex-post studies to justify these assumptions.

The model-based ex-ante evaluation of energy and climate policies (e.g. Lutz et al. (2018) for Germany, Pollitt et al. (2017) for the EU) often takes those parts of the models as exogenous, that could deliver information on the rebound effects. In these studies, technically oriented bottom-up models (energy system models) are often used to calculate the energy efficiency improvement on a detailed micro or meso level. The resulting energy efficiency increase, which should - but not necessarily does - include direct rebound effects, is in a next step an exogenous input for efficiency or policy scenarios in the macroeconomic models (CGE or macroeconometric). As some energy-related parts of the macroeconomic models are set exogenously for this model linkage, rebound effects in these policy analyses are small or zero by definition. Ex-ante policy modelling in *ReCap* has to ensure, that rebound effects will be fully captured.

To summarize, the evidence about the magnitude of economy-wide rebounds from ex-ante modelling studies is weak. Even similar approaches report a wide range of economy-wide rebound effects depending on assumptions about elasticities of substitution, the model type and coverage. Some authors find higher rebound effects for countries with a high share of domestic energy production and for developing countries.

3.3 Empirical ex-post studies

Only few studies have investigated rebound effects on a macroeconomic level using empirical data. To prove a causal relationship between energy efficiency and energy use, one needs to ensure that the historical increase in energy consumption is not due to other factors such as GDP growth or environmental effects (Gillingham et al., 2016). A causal attribution of the economy-wide rebound effect is in fact challenging and has thus been addressed only by a small number of econometric investigations. Nevertheless, an econometric approach might be advantageous over computable general equilibrium models as these are very sensitive to a-priori assumptions as discussed above.

Comparing the results of the few ex-post studies on rebound effects is challenging as there is no established consensus on the methodologies to measure energy efficiency in practice, despite the fact that the term is in trite use. Previous approaches utilize a diversity of methods, most prominently the Index Decomposition Analysis (Lin & Du, 2015b), simple ratio indicators (Ang, 2006) and Frontier Analysis (Adetutu & Weyman-Jones, 2016).

Shao et al. (2014) estimate China's economy-wide energy rebound effect over the period 1954-2010. They define the rebound effect based on the IPAT1 equation and employ a state-space model that captures the dynamic relationship among the output, growth rates of technological progress, capital, labour and energy, to estimate the technological growth rate. By using a latent variable approach they certainly overcome shortcomings of previous studies that used the Solow remainder method (e.g. Li and Yonglei, 2012) or the Malmquist index method (e.g. Lin and Liu, 2012). However, Lind and Du (2015b) highlight several technical shortcomings of their approach, e.g. that the authors approximate the contribution of technological progress to energy consumption instead of energy efficiency. Alternatively, they propose a multi-level index decomposition analysis (IDA). Their results reveal that during 1981-2011 energy rebound effect in China is between 30% and 40%. However, their method still falls short in disentangling the interactions between energy efficiency improvement and output growth.

Galvin (2014) uses the ODEX index from the Odyssee data base which is also approximated via IDA and estimates rebound effects for household energy consumption in the EU28 countries. The study offers a closer, qualitative analysis for the case of Germany, estimating a rebound effect of 21.6%. However, the author himself points out that the results are “broad-brush” rebound effects as energy efficiency increases are assumed to be the only determinants of the changes in energy consumption. Also Antal and van den Bergh (2014), who study the “re-spending rebound” and Holm and Englund (2009) who define a “gross rebound effect” seem to neglect that growth effects also contribute to the evolution of energy consumption.

Adetutu & Weyman-Jones (2016), propose a two-stage approach for the estimation of the economy-wide model. First, a stochastic frontier model is applied to estimate energy efficiency and in the second stage a dynamic panel model is used to estimate the magnitude of the short and long run, economy-wide rebound effect. For a group of 55 countries analyzed over the period 1980-2010, their results vary from 36-90%. For Germany they claim a rebound effect between 71 and 80%. Most recently, Bruns et al. (forthcoming) use a structural vector autoregressive (SVAR) model to estimate the economy-widerebound effect with a minimum of a priori assumptions. They apply the SVAR to U.S. monthly and quarterly data, finding that after four years rebound is around 100%.

While the empirical literature on rebound effects is growing fast, it is clear that an empirical account of economy-wide rebound effects remains a challenging endeavor that will require innovative solutions. Moreover, given the current availability of data one has to content oneself with substantial variations regarding the estimates of the size of the rebound effect that vary widely within a range from 20% to 100%.

A greater understanding of rebound effect drivers is essential to further assist policy makers. Adetutu et al. (2016) find larger effect magnitudes for developing than for developed countries, which also include backfire. They see the growth trajectory of the developing countries as a possible reason for the difference: Higher and even growing energy consumption eventually leads to situations in which energy savings are “re-invested” at a higher rate to foster further growth. Holm and Englund (2009) compare the US and six European countries and make differences in population growth rate and in absolute levels of per capita energy use responsible for the variations in the size of the rebound effect.

However, it is in general difficult to derive policy implications and rebound drivers from macroeconometric models due to the high aggregation level. Consequently, several authors as for example Sorrell (2007) and Adetutu & Weyman-Jones (2016) underline that a sectoral analysis across different countries in order to decompose the economy-wide rebound effect into its underlying sources could be helpful for this purpose.

Similar as in the case of ex-ante models, it is difficult to draw general conclusions from such ex-post studies. There is a consensus, however, on the existence of positive economy-wide rebounds but the estimated magnitudes vary widely. In addition, there are few insights so far into the main factors determining the size of the rebounds. The average income level, the speed of economic growth and the speed of population growth have been found to be important aspects in some investigations. However, in order to sharpen conclusions on the magnitude and the drivers of economy-wide rebounds, further research is needed (see section 5.3).

3.4 Summary

The discussion in this section has shown that analyzing the economy-wide rebound from the top down is by no means easy. At the same time, there are only relatively few studies within the strands of research covered in sections 3.1 Theoretical macroeconomic approaches and 3.3 Empirical ex-post studies. Therefore, there is significant room for future research on top down approaches. Additionally, a major challenge lies in comparing the different approaches and analyzing, which assumptions and which characteristics of the economies investigated are responsible for the wide range of findings regarding the size of the economy-wide rebound. The lack of such an analysis also makes it hard to formulate general insights from the top down approaches. However, one overall finding seems to be that the speed of economic growth tends to be important for the size of the economy-wide rebound. This has been pointed out by the theories discussed in section 3.1, as well as by empirical research covered in 3.3 Empirical ex-post studies. Additionally, the elasticity of supply of energy has been highlighted both, by theoretical approaches in 3.1 Theoretical macroeconomic approaches and the ex-ante models in 3.2 Empirical ex-ante models.

4. Proposed policy measures to mitigate rebound effects

As the previous sections 2 and 3 have demonstrated, there is a rich theoretical and empirical research literature on rebound effects. In contrast, only few academic contributions have spelled out specific policy implications that follow from these findings. This section summarizes the most relevant policy recommendations from five policy-oriented studies (Maxwell et al., 2011; Santarius et al., 2018b; Semmling, et al., 2016; van den Bergh, 2011; Vivanco, Kemp, van der Voet, 2016) that explicitly deal with rebound mitigation options for policy-making. These studies are complemented by the few policy recommendations that can be found in the broader academic literature dealing with rebound effects. We first summarise the generic or meta insights from the broader literature (4.1) before then turning to discussing the five-policy oriented studies and classifying their recommendations into different instruments types that can be used at different economic levels (in sections 4.2-4.4).

4.1 (Meta) Policy recommendations in the rebound literature

4.1.1 Importance of recognising rebounds in policy making

An immediate conclusion to be drawn from the rebound literature is that policy makers need to consider and address rebound effects when designing energy efficiency policies while aiming for energy conservation. Sorrell (2007), Madlener and Alcott (2009), Maxwell et al. (2011), Saunders (2013), as well as Vivanco et al. (2016) underline the importance of recognizing and accounting for rebound effects in the process of policy development and evaluation. According to Vivanco et al. (2016), however, the scientific community has so far been unsuccessful in inducing policy makers to introduce measures to contain and prevent rebounds. In order to foster the consideration of rebounds, they suggest the creation of simple, transparent and ready-to-use assessment and benchmarking toolkits that help policy makers to estimate the implications of rebound effects. However, this is not straightforward given the difficulty of defining and measuring rebounds, the lack of shared definitions (see section 2) as well as the divergence of findings in the existing literature on the scale of rebounds in different contexts (as discussed in sections 3.3-3.3. Also Madlener and Turner (2016) stress the complexity of assessing rebounds and point out that decision-makers should be cautious with regard to false interpretations of insights, or unjustified comparisons across studies, sectors and regions.

4.1.2 Additional policies complementing energy efficiency measures required

Another generic insight from the rebound literature is that efficiency-stimulating instruments need to be complemented by additional policy measures in order to dampen rebound effects. The large majority of scholars stresses that measures to increase energy efficiency need to be complemented by changes in economic policy instruments, such as carbon and energy taxes (Brännlund et al., 2007; Hanley et al., 2009; Steve Sorrell, 2007; Turner & Hanley, 2011; van den Bergh, 2011). Among the few deniers, Broberg et al. (2015) claim that technological efficiency improvements would still have significant impacts on energy savings without such measures. In contrast, Greening et al. (2000) claim that climate policies that rely on energy efficiency technologies need reinforcement by market instruments and other incentive mechanisms, as otherwise a significant proportion of the achievable carbon and energy savings could be lost to rebounds. Following Birol & Keppler (2000b), Hanley et al. (2009) point out that policies concerning technology and relative prices complement each other well, given that energy efficiency stimuli may create the potential for energy taxes to be levied without generating the adverse effects on economic activity that would be otherwise expected.

4.1.3 Appropriate policy design and policy mix

The rebound literature stresses the importance of an appropriate instrument design and policy mix for avoiding undesired outcomes of efficiency improvements. For instance, Barker et al. (2009) stress the need for ‘portfolios of policies’ that complement behavioral change following energy savings. According to Vivanco at el. (2016), key aspects of policy design include the correct implementation of economic instruments with regard to tax spending, the scope of schemes and the level of allowances. They also call for a mix of policies that simultaneously address the efficiency, the structure and the overall level of consumption, or put differently, the energy intensity, the composition and the magnitude of economic activity. Potential solutions are specified by Semmling et al. (2016) who distinguish between policy instruments that are rather prone to trigger rebound effects (e.g. subsidies, funding instruments, efficiency standards), instruments that are less prone to rebound effects (e.g. permits, voluntary agreements, public procurement) and rebound mitigating instruments (e.g. taxes and fees, tradable certificates, information and communication tools). They point out (psychological and financial) factors that may influence the extent of rebound effects and suggest how to address these factors by a combination of different measures (i.e. a well-designed policy mix).

4.1.4 A typology of rebound mitigation policy instruments

The rebound mitigation instruments discussed in the literature are no different from general policy instruments for energy conservation, as they primarily tackle rebound effects either by supporting energy efficiency improvements or by incentivizing energy savings. Effective rebound mitigation is rather a question of appropriate instrument design and the right policy mix, than of implementing one specific instrument. The environmental economics literature often distinguishes between three families of policy measures: regulatory ('sticks'), market-based ('carrots') and soft instruments ('sermons') (Borras & Edquist, 2013; Sterner, 2013). To get an idea of the instruments available for rebound-proof policy mixes, the most relevant rebound policy measures discussed in the literature (see Table 3 in the Annex) are further classified according to which economic level they mainly address in line with the typology developed above:

micro-level instruments affect individual decision units (firms or households) or markets,
meso-level instruments affect multiple markets or sectors,
macro-level instruments affect the economy as a whole.

The assignment of each instrument type to one economic level is not trivial, since various economic levels may be affected and the reach of an instrument oftentimes depends on specific details of its design. Nevertheless, Table 2 attempts to map the most relevant policy instruments in the literature to the levels of the economy based on considering its main target group.

Table 2: Policy instruments to tackle rebound effects at different economic levels

	Micro-level	**Meso-level**	**Macro-level**
Regulatory instruments	Efficiency standards	Carbon caps (for certain sectors)	Economy-wide carbon caps
Market-based instruments	Rebates and subsidies Product-specific taxes	Tradeable permits (within certain sectors) Tradeable permits (within (e.g. air passenger duties) Support for R&D and innovations	Economy-wide cap and trade schemes Economy-wide energy pricing taxation
Soft instruments	Sustainability communication (e.g. individual feedback, trainings and campaigns, labelling) Defaults / nudging Promotion of sustainable Lifestyles and moral suasion	Sector-specific voluntary agreements (e.g. energy efficiency agreements in the Netherlands)	

The following sections discuss the different types of policy instruments available to mitigate rebounds in more detail.

4.2 Regulatory instruments

Regulatory instruments comprise direct regulations that restrict the scope of action by forms of rationing, prohibition or technical specification enforced by an authority. Absolute caps of carbon emissions and product-specific energy efficiency standards are the main regulatory instruments for tackling rebounds that are discussed in the literature.

4.2.1 Absolute and economy-wide carbon caps

The advice to make use of absolute and economy-wide carbon caps in order to avoid rebound effects is popular among scholars. If the energy use is restricted by binding upper limits, there can in theory be no rebound effects, because allowances remain fixed irrespective of the overall efficiency of the economy. Yet, the scope of caps is usually not encompassing all economic sectors (and economies internationally) and when caps apply only to individual sectors or countries, the displacement of emissions to unregulated sectors or other countries through “carbon leakage” can reduce the global effectiveness of these caps. Also, a moratorium (e.g. on the use of coal) works very much like a sector-specific cap, with similar implications regarding possible leakages. Without a global implementation, economies that implement ambitious saving targets may lose (international) competitiveness due to an increase in energy prices. Moreover, unless absolute decoupling can be achieved, a strict and declining national allowance over time does not accommodate economic growth. Due to the importance of energy prices for economic growth (and social stability), policy makers are likely to refrain from setting ambitious absolute caps (the example of Chinese energy pricing is discussed by Lin & Du, 2015a). Therefore, although this instrument may be effective in addressing different kinds of macroeconomic rebounds, including induced growth, it is politically challenging due to its potentially significant social costs.

4.2.2 Contingent and dynamic energy efficiency standards

Efficiency standards are usually specified at the level of product categories. They define a maximum allowable level of energy consumption per unit of output (e.g. minimum efficiency requirements for heating and cooling products) or prohibit technical solutions that are particularly energy-consuming (e.g. standby requirements, incandescent light bulbs). These requirements are supposed to raise the average energy efficiency in a specific market by phasing out the most inefficient products. If not designed well, mandatory efficiency standards can have considerable rebound effects and may even backfire. Semmling et al. (2016) point at associated changes in the cost structure, positive scale effects and psychological factors that may induce increased consumption. To avoid the crowding out of smaller devices, they call for size and performance contingent standards. They also call for informing consumers about the behavioural changes that are needed to exploit the potential of more efficient technologies.

In order to reduce the (high) risk of triggering rebound effects, Santarius et al. (2018b) suggest to dynamically upgrade efficiency standards wherever possible and to embed them into a broader policy mix.

4.3 Market-based instruments

Market-based instruments or economic instruments use markets, prices and other economic mechanisms to provide incentives for the reduction of energy consumption. As complementary instruments, they may limit the rebound effects of energy efficiency measures. Examples include carbon or energy taxes at different levels of the economy (sector= meso or national=macro), rebates and subsidies, emissions trading and other tradeable permit systems.

4.3.1 Globally implemented cap and trade schemes

Leaving problems of political feasibility aside, from an economic point of view, a cost-effective way of implementing absolute saving targets is to combine caps with trading schemes (Semmling et al., 2016; Vivanco et al., 2016). In theory, properly designed and implemented schemes may tackle macroeconomic rebounds by ensuring the compliance with overall energy targets, while allocating the saving efforts to the most efficient solutions. With such instruments in place, the energy price is endogenously determined by the market, creating stronger market incentives to save energy when approaching the emission limit. Vivanco et al. (2016) emphasize that these systems are rebound-proof only in the case that the scheme encompasses all economic sectors, which is usually not the case. Moreover, the implementation of a global emission schemes appears to be unlikely, and as long as some emission sources, or some countries, are not part of the cap, leakage could still occur (Santarius et al., 2018b). Nevertheless cap and trade instruments are the preferred policy option for limiting overall energy consumption following efficiency improvements at the macroeconomic level.

4.3.2 Smart and flexible energy taxation and other pricing instruments

Another popular macroeconomic policy instrument is a carbon or energy tax (Saunders, 2011; Vivanco et al., 2016). 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 to avoid income effects and re-spending. In this way, an economy-wide tax may curb direct and indirect rebound effects at the macroeconomic level simultaneously. Many scholars see carbon or energy pricing as an inevitable part of any effective climate policy package. However, Maxwell et al. (2011) stress that it is crucial that tax proceeds are not spend in a way that induces growth. Such an economy-wide tax would lead to a decrease in economic output and an increase in unemployment rates, thus creating considerable social costs. Santarius et al. (2018b) therefore point out three challenges related to such a tax: (1) it addresses only financial rebound mechanisms; (2) the social costs could be considerable,

(3) taking social trade-offs into account, a general tax would not be feasible, but have to be sector-specific. Considering these trade-offs, Saunders (2011) recommends using sector-specific taxes or fees and to redistribute tax proceeds in order to reduce labour costs. Product-specific taxes (e.g. on vehicles) may address income or re-spending effects at micro-level. The value of rebates and subsidies for energy-efficient products (e.g. on electric vehicles) as market-based instruments to address rebounds crucially depends on their design, as they can also be sources of new rebounds. Vivanco et al. (2016) recommend using revenues of environmental taxations to finance these programs and adjusting the magnitude to the use of the product.

4.3.3 Targeted support for R&D and eco-innovation

It is common sense that the existence of rebound effects is no reason to stop developing energy-efficient technologies, but to revise the expected impacts on energy use (Maxwell et al., 2011). Engineering alone will however not provide the required decoupling. Rebound effects tend to be larger for energy-efficient general-purpose technologies (Herring & Sorrell, 2009; Steve Sorrell, 2007) and cost saving technologies (Vivanco et al., 2016). Vivanco et al. (2016) suggest selectively promoting only innovations that entail moderate cost reductions or even increases, and targeted eco-innovation. However, according to Grepperud and Rasmussen (2004), policy support for efficiency innovations should not necessarily be directed towards sectors with weak rebound effects, since the social desirability of policy-induced innovation will in general depend on the presence of market imperfections.

4.4 Soft instruments

Soft policy instruments rely on voluntarism, learning processes and procedural change, rather than direct regulatory control or economic incentives. Prime examples are consumer information and communication tools as well as voluntary agreements at the sector level.

4.4.1 Promotion of Sustainable lifestyles

Sufficiency strategies, such as reducing purchasing power by working or earning less, are a simple and effective way to mitigate re-spending rebound effects (Martínez-Alier et al., 2010). However, the adoption of sufficiency-based lifestyles faces strong barriers of social acceptance, mainly because of hard to overcome consumer habits (Sorrell, 2010). The effective promotion of sustainable lifestyles would thus have to start by encouraging changes in consumption patterns and increase the social acceptance of frugal behaviour.

4.4.2 Sector-specific voluntary agreements

As prime example of soft policy instruments, voluntary agreements are self-commitments by industry to meet certain standards or environmental goals. Long-term voluntary agreements have been achieving industrial energy efficiency improvements in the Netherlands (Rietbergen et al., 2002). If, however, the voluntary commitment is not ambitious enough, efficiency gains can be offset by increased consumption of the resource. The less ambitious the commitment, the greater the risk of rebound effects (Semmling et al., 2016).

4.4.3 Sustainability communication, consumer information und persuasion

Sustainability communication measures aim to influence the knowledge and values of consumers and producers (Santarius et al., 2018b). Such measures include environmental education, sustainability advertising campaigns and eco-label schemes, as well as environmental management systems, environmental audits and green marketing. Semmling et al. (2016) classify information and communication instruments as measures appropriate to counteract rebound effects. In combination with other policy measures (such as taxation or mandatory requirements), these instruments help avoiding psychological rebounds, creating awareness and social acceptance. 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. In the context of rebound mitigation, providing consumers with feedback on their individual consumption levels is seen as promising instrument to raise awareness (Vivanco et al., 2016) and counteract psychological rebounds (Santarius et al., 2018b; Semmling et al., 2016). Eco-labels are supposed to help consumers identifying environmentally-benign products. Other consumer-influencing instruments include trainings and campaigns (Semmling et al., 2016) implicit suggestions (nudging and default setting) as ways to influence the behavior and decision making of consumers (Michalek et al., 2015).

4.5 Summary

There is a fundamental trade-off between the efficacy of policy instruments in mitigating rebound effects and the involved economic costs. Instruments at the meso- or microeconomic can be precisely targeted at reducing direct rebound effects in specific markets or sectors, but cannot prevent overall re-spending effects. As otherwise carbon leakage is possible, the effective limitation of indirect rebound effects thus needs to take place at the macroeconomic level. At the same time, the social costs are highest for macroeconomic instruments, since restrictions on resource use will affect the economy as a whole and limit economic growth. From an economic perspective, a given carbon cap is better enforced by market-based instruments (trading schemes) than by regulatory instruments, since flexible market allocation minimizes the overall costs of compliance. Soft instruments shift the responsibility for energy conservation down to the level of the individual decision unit and therefore need no collective decision considering the social costs. This might be a viable and effective policy option for mitigating rebound effects in the presence of intrinsically motivated actors, incomplete or asymmetrical information. There is no silver bullet instrument for tackling rebound effects. In fact, advantages and disadvantages of different policy instruments and their possible combinations need to be considered carefully. This is challenging in the absence of empirical studies of the effectiveness and efficiency of different porfolios of policies to mitigate rebound effects.

5. Reseach gaps and planned contributions of ReCap

In this section, we point out several research gaps based on the discussion in sections 2-4 and show how the research project *ReCap* plans to contribute to filling these gaps. Based on our analysis of different strands of the literature that contribute to understanding and addressing economy-wide rebound effects, we identify several promising research areas.

5.1 Macroeconomic theories

As we have seen in section 3.1, the literature applying macroeconomic theories to the question of the size of the economy-wide rebound is still very limited. While Brookes' contributions are of major importance, they do not make use of a coherent macroeconomic theory (but rather put forward several theoretical arguments). The contributions by Saunders' are by far the most stringent. Additionally, the discussion by Sorrell and Dimitropoulos (2007) is a good starting point for further research. However, such contributions still leave significant room for future research, in particular in two areas.

First, there are several prominent neoclassical theories on economic growth and the environment, that can be applied to the question of the determinants of economy-wide rebounds – in particular endogenous technological change theories, such as the theories discussed in Aghion and Howitt (2009) and directed technical change theories.

Second, a rigorous application of the theories of ecological economics to economy-wide rebound could help to identify the determinants of its size. In combination with the existing research and the additional application of neoclassical theories, it would become feasible to determine which factors determine the size of the economy-wide rebound from a theoretical perspective.

An additional area of research would be to point out the (theoretical) characteristics of an economy with a low economy-wide rebound.

As part of ReCap we plan to investigate several of these options but have not yet made a final decision on this matter.

5.2 Empirical studies of rebounds and elasticities at firm and sector levels

Comparing the research on microeconomic, mesoeconomic and macroeconomic rebounds (see section 2), one can observe a major discrepancy in the number of available empirical analyses as pointed out above. On the one hand, there are many investigations of microeconomic rebounds at the household level. For all other levels, the literature only offers scarce empirical evidence. To date, very few investigations at the firm level and only few at the mesoeconomic level exist. To the best of our knowledge, there are no empirical investigations of macroeconomic rebound effects – which in all likelihood is due to the fact that such investigations, are very difficult to conduct methodologically. These research gaps are also significant as the effectiveness of econometric models on the economy-wide rebound can be increased if they can be linked to „bottom-up“ models describing effects at the micro- and mesoeconomic levels (e.g. Sorrell (2007), Adetutu & Weyman-Jones (2016)).

The bulk of rebound research ignores the correlation between energy efficiency and energy use on the sector level (Santarius (2016a)). We focus on explaining the heterogeneity between sectors and firms, using a panel on cost and investment data of the German manufacturing industries, including a host of variables (e.g. production output, input factors as well as value added in different graduations) for around 16.000 firms over a period of 21 years (1995-2016) provided by the German Research Data Centre (RDC) of the Federal Statistical Office and Statistical Offices of the Länder. To achieve this goal, it is vital to approximate energy efficiency for different firms. Using energy intensity as a proxy for energy efficiency has been criticized by various authors (e.g. Filippini and Hunt (2011); Saunders (2013)). We thus try to estimate energy efficiency by harnessing the relative position of a firm's energy use in comparison with competing companies.

First, we apply a Stochastic Frontier Analysis, which allows us to gain estimates on the energy efficiency of individual firms within their respective sector. A sound estimate for energy (in)efficiency with respect to the energy efficient production frontier for a firm can then be obtained by combining the mixed models framework (Fahrmeir & Lang, 2001) and the structural equations framework (Bollen, 1989; Thaden, 2017). Thereby the energy efficiency of each firm can be defined as an index that can subsequently be used to assess the effects of gains in energy efficiency at the firm (micro), subsector and sector (meso) level.

In a second approach, we identify the relative energy efficiency position of a firm exploiting the conditional distributions of resource and energy consumption of the firms. Thereby, we can assess whether a higher energy efficiency level of a firm reduces or encourages energy consumption in the subsequent period. With the approach, we aim to test the implicit hypothesis that the firms that achieve competitive advantages due to energy efficiency improvements will try to extend their production subsequently in order to achieve higher profits and thereby eventually induce rebound effects.

Besides applying new techniques to estimate energy efficiency, the results comprise estimations on elasticities of substitution between energy and other production factors, which can be fed into the PANTA RHEI model. Additionally, the relative analysis of efficiency and rebound drivers at the sector level is meant to test hypotheses that have been identified in the theoretical analysis and can eventually help to develop a set of rebound-mitigating policy measures.

5.3 Empirical ex-post studies at the macroeconomic level

There is only a limited number of contributions estimating the economy-wide rebound ex-post, using aggregated variables (see section 3.3). At the same time, it is also highly challenging to conduct such investigations. Nonetheless, these approaches have the advantage of not depending on a large variety of assumptions, as do the ex-ante approaches. Therefore, improving the existing approaches is a promising line of research to come closer to an estimate of economy-wide rebound effects. Two steps seem most promising: First, there is no in-depths analysis of the strengths and weaknesses of the existing approaches. This would, however, be needed to decide upon which approach to use in the future. Second, based on our analysis of this literature, dynamic time series models, as the SVAR-approach (Bruns et al., forthcoming), seem to be promising, not only because the approach depends on a minimum number of a-priori assumptions but also because the included variables are regarded as endogenous and therefore can evolve in response to a shock.

Accordingly, we apply an extended SVAR method to European countries and the US. In a first step we get a rough estimate for the economy-wide rebound effect that goes beyond the partial equilibrium analysis. Following Bruns et al. (forthcoming) we estimate the economy-wide rebound effect by means of a structural vector autoregression (SVAR) with an empirically identified contemporaneous causal structure (Gouriéroux et al., 2017). This approach is data-driven and relies on a minimum of a priori assumptions. The multivariate time series model allows us to identify the evolution of economic output, energy prices and energy use in response to exogenous energy efficiency shocks and thereby the size of the rebound effect can be approximated.

The preliminary results of the SVAR models deliver a great deal of useful structural information, especially considering the simple modelling structure. However, the sparse set of specific time series commonly included in the approach potentially leads to omitted variable bias. Unfortunately, the inclusion of additional variables is limited due to degrees-of-freedom constraints. We try to overcome these difficulties and condition the data analysis on a richer information set by augmenting the SVAR with factors estimated from a large, monthly frequency, macroeconomic data set (Bernanke et al., 2005). This dataset contains information on the state of the economy as for example the labour market, consumption, housing or exchange rates (McCracken & Ng, 2016). The latent factors are extracted from the data set by a principal component analysis.

We apply the model to a number of European countries and the US to compare the dynamics following energy efficiency shocks. Preliminary results indicate high rebound effects (between 80-100%) for all analysed countries after a time period of four years.

5.4 Empirical ex-ante models

There is a substantial number of studies to estimate rebound effects at the meso and macro level in macroeconomic models (3.2). However, consensus even about the magnitude of effects is missing. Different assumptions and factors such as elasticities of substitution between energy and other production factors, elasticities of substitution between other production factors, as well as trade elasticities are crucial for the resulting rebound effects. Also, production structures, energy intensity and general assumptions behind the models used can play a role. There is some understanding about the role of different production factors and parameters for rebounds, but "econometrically estimating the effect of the general equilibrium [macro] rebound is challenging" (Boehringer & Rivers, 2018). We identify four ways how existing models can be improved.

(1) One major reason is that sound econometric estimates of substitution elasticities are missing: In all studies elasticities of substitution are largely responsible for the magnitude of rebound effects. The substitution elasticities of energy in the production process are of great importance, regardless of the type of production function used. In the case that foreign countries are also included in the analysis, Armington elasticities, which describe the preference for domestic products, also influence the rebound effects via bilateral trade. Substitution elasticities will be taken from empirical ex-post estimations (see 5.3 Empirical ex-post studies at the macroeconomic level).

(2) Investments and costs needed to reach additional energy efficiency in an already highly efficient market economy are often neglected. For example, in ex-ante approaches, the economy and its sectors adjust smoothly to the positive efficiency "shock" via reduced costs and prices in the more efficient industries, as substitution between factor inputs is possible in no time according to substitution elasticities. Sometimes lower short-term and significantly higher long-term substitution elasticities are used to calculate the respective effects. Rigidities due to long-life cycles of energy intensive capital stocks are thus accounted for quite generically or not at all. While in the majority of the models considered, the causal shock is set as an autonomous increase in energy efficiency at no cost, Allan et al. (2007) show in a sensitivity analysis that the assumption of needed investment has a drastic effect on the level of the rebound and can even counteract it completely.

(3) In most ex-ante modelling studies energy efficiency improvement is detached from energy efficiency policy (section 4). Only Barker et al. (2009) point out the possibility of specifically attributing energy savings to individual policy measures (with associated costs and behavioural adjustments). Specific policies as described in section 4 have to be considered in the modelling to calculate respective rebound effects. If the influence of policies - and the underlying investment - on the magnitude of the rebound effects can be separated, rebound-proof policies can be designed and tested.

(4) When looking at a national economy, it is also important which products are additionally consumed by consumers, who have an increased household income, or produced by industry. Barker et al (2009) point out that these may contain a very small portion of domestically produced energy, which makes the national rebound lower, but increase energy consumption abroad. In the case of the UK, this applies in particular to imported cars and long-distance travel. For similar reasons, a differentiation will also be made according to energy carriers considered.

In the ReCap project, modelling of rebound effects in the national macroeconometric model PANTA RHEI will separate these effects with a focus on the specific energy and industry structures for

Germany by various sensitivity analyses and by taking capital costs and different policy instruments (5.5) explicitly into account. Important parameters such as elasticities of substitution will be based on empirical ex-post analysis (5.3).

5.5 Appropriate policy mixes to reduce rebounds

The review of policy recommendations in the rebound literature (section 4) has demonstrated the need for complementing energy efficiency improvements with appropriate policy instruments in order to mitigate associated rebound effects. Apart from some notable exceptions, there still is little research on how policy can tackle this problem adequately.

It was pointed out in the literature that there is no single “silver bullet” instrument that can rule out the occurrence of rebound effects. On the contrary, micro-, meso- and macro-level instruments have particular advantages and disadvantages with regard to the effectiveness and the involved costs of addressing different rebound mechanisms. Section 4 gave an overview of the range of instruments available for targeting different rebound effects and concerned groups of actors at multiple levels. The literature clearly suggests using context-specific mixes of complementary policy instruments in order to tackle different types of rebound effects simultaneously. So far, research on what such portfolios could look like in practice is scarce.

One major obstacle to avoid rebounds through strict policies of various kinds is political and social acceptability, which needs to be one important consideration in designing appropriate policy mixes. There is however little research on the question of political feasibility of instrument mixes to tackle rebounds so far.

ReCap takes a political practice-oriented approach in developing different sets of policy measures that are at the same time politically feasible and rebound-proof. New formats of environmental governance and process design must take into account the contextual constraints and practical policy implementation issues at an early stage. We therefore bring together practitioners from politics, business and civil society to discuss potential interventions in a transdisciplinary forum, the Policy Innovation Lab. Together with these stakeholders, the project team develops proposals for measures that may limit the economy-wide rebound effect. The probable impacts of these policy mixes will be assessed using the PANTA RHEI model. The results will be fed back into the Policy Innovation Lab to improve upon the suggested set of policies. In this manner, the Policy Innovation Lab allows pooling the distributed knowledge of practitioners and link our research to concrete actor contexts and practical experiences.

6 Conclusions

The central question of this discussion paper is: what determines the size of the economy-wide rebound and how can it be limited? We have analyzed the literature on the first part of the question in sections 2 and 3, dividing the literature into bottom up and top down approaches. In section 4 we have discussed policy considerations and section 5 discussed how the project *ReCap* helps to fill several remaining important research gaps. In the following we summarize the most important results, relate them to each other and to future research in *ReCap*.

In the bottom up approaches, we have introduced a new taxonomy of rebounds. Following existing taxonomies, rebounds are categorized into micro-, meso- and macroeconomic effects. Importantly, we differentiate rebound effects at different levels While the rebound effects take place at the respective level (e.g. microeconomic rebound effects take place at the micro level, etc.), the total rebound at a certain level is determined by the rebound effects at that level and at lower levels. The taxonomy makes sure that double counting is prevented as it traces all rebound effects to the micro level – while working their way through the higher levels, additional effects come into play.

At the micro level of households, the size of the rebound depends on households' decisions – how much of savings they spend and on what type of goods and services. The literature distinguishes between direct and indirect effects. There are many empirical investigations on the direct effect, estimating it somewhere between 10 – 30%. The investigations on indirect effects also find a broad range of sizes. Despite their importance, there are no empirical investigations of rebounds at the micro level regarding firms. *In the research project ReCap, we make use of a large data set on firms to contribute to this question. We estimate the energy efficiency of single firms with respect to the energy efficient production frontier. This allows us to develop an indicator for energy efficiency, which in turn facilitates to investigate rebound effects on the firm level.*

At the meso level, we have identified three central mesoeconomic rebound effects that are discussed in the literature. Each refers to a different type of sector or market – to single energy markets, to sectors for intermediate goods and services and to sectors for final goods and services. However, there are no empirical investigations of such single mechanisms. Instead, the empirical literature looks at the total rebound of entire sectors, not differentiating between intermediate and final goods. Once again, the sizes of rebounds vary widely. The few investigations that examine several sectors indicate that sectors with higher energy-intensity experience larger rebounds. *In ReCap, we add to this literature by analysing a panel on cost and investment data of the German manufacturing industries provided by the German Research Data Centre to explain the heterogeneity between more and less energy-intensive sectors.*

There are four macroeconomic rebound effects – referring to the macroeconomic multiplier, general market price of energy, international trade and relocation and the international energy market. While these effects are explained theoretically in the literature, there are – as in the case of mesoeconomic rebounds – no empirical investigations of such single rebound effects. The reason is probably in both cases, that empirical investigations of such single rebound mechanisms are very difficult methodologically. Instead, there are – as for the meso level – empirical investigations of the total rebound at the macro level (which we covered in section 3.3, discussed again below).

An important conclusion from the analysis of this literature on micro-, meso- and macroeconomic rebounds is that investigating single rebound effects is very difficult. Instead, the "total" rebound can be examined on a specific scale – regarding households, firms, sectors or entire economies. Which of the specific rebound effects is responsible for size of the "total" rebound at a specific level, is difficult to investigate. It is even possible that important rebound effects were not indicated – or at least this cannot be ruled out by existing empirical investigations.

In terms of the top down approach to assessing economy-wide rebound effects, we have differentiated between three types of research (see section 3). All three of them are still limited in number. The theoretical approach, mostly using theories of economic growth, indicates that economy-wide rebound is expected to be large, often predicting backfire. Central determinants of the size of the rebound are (1) the role of energy for economic growth (the output-elasticity of energy and the additional energy demand due to increases in output), (2) the elasticity of supply of energy and (3) the embodied energy in new technology. *In ReCap, we apply additional growth theories to the question of economy-wide rebounds and investigate which assumptions change the size of the rebound effect. We put special importance on contributions from ecological economics.*

In the ex-ante approaches, evidence about the magnitude of economy-wide rebounds modelling studies is weak. Even similar approaches report a wide range of economy-wide rebound effects. *In ReCap, we adjust the model PANTA RHEI to conduct an ex-ante estimation of the economy-wide rebound. The model is extended to take into account four central weaknesses of most existing models: (1) Sound estimates of elasticities of substitution, (2) investments and costs needed to achieve additional energy efficiency, (3) the impact of the policy generating the increase in energy efficiency, and (4) additional consumption by households experiencing additional income due to a rebound effect.*

It is difficult to draw general conclusions from ex-post studies. There is a consensus, on the existence of positive economy-wide rebounds but the estimated magnitudes vary widely. Also, there are so far few insights in the main factors determining the size of the rebounds. The average income level, the speed of economic growth and the speed of population growth have been identified as important aspects in some investigations. In order to sharpen conclusions on the magnitude and the drivers of economy-wide rebounds, *in ReCap we apply an extended version of the most promising method (SVAR) to European countries and the US.*

Due to the high heterogeneity of perspectives on determinants of the size of economy-wide rebounds both within each line of research (theoretical, ex-ante and ex-post) as well as between them, it is difficult to draw general conclusions. Only the speed of economic growth plays an important role for the size of economy-wide rebounds across all strands of research. Its exact role, however, remains unclear as well. Therefore, integrated analyses are needed regarding the question, how the different results from these different strands of research can be explained.

In terms of the question of how policy action can limit rebound effects, our review of the literature has demonstrated the need for complementing energy efficiency improvements with appropriate policy instruments in order to mitigate associated rebound effects. Section 4 has also shown that policy proposals exist for all levels - micro- meso- and macro. At the same time, there is not a single “silver bullet” instrument that can rule out the occurrence of rebound effects. Additionally, a major obstacle to avoid rebounds through strict policies of various kinds is political and social acceptability. Therefore, we need politically feasible, context-specific mixes of policy instruments in order to tackle different types of rebound effects simultaneously. So far, research on such policy-mixes is scarce. *That is why ReCap takes a practice-oriented approach in developing different sets of policy measures that are at the same time politically feasible and rebound-proof. In ReCap, practitioners from politics, business and civil society, as well as scientists, are brought together to discuss potential interventions in a transdisciplinary forum.*

The analyses of sections 2 and 3 have shown that theoretical arguments for rebound effects and empirical investigations have barely been integrated so far. In section 2 and 3.1 we have seen that there are numerous arguments how rebound effects may take place. Each of them makes sense from a theoretical perspective. As long as it is not possible to test them empirically, it will be difficult however to improve the understanding of the determinants of the economy-wide rebound in the real world. Additionally, the relation between single micro-, meso and macroeconomic rebound effects (in section
2) and the determinants of the economy-wide rebound in growth theories (section 3.1) remains unclear. In a similar manner, the precise relation between the policies proposed and the rebound effects described in our taxonomy remains unclear. In order to better *understand* the determinants of the economy-wide rebound and to better tackle them by appropriate policy action, it is therefore necessary to better integrate the different strands of research. In section 5 we have indicated several ways in which *ReCap* attempts to contribute to this endeavor. All in all, this makes ReCap an incredible wide-ranging and challenging research project on a difficult topic and we are looking forward to your constructive feedback and suggestions for improvements during our workshop discussions.

7. Annex

Table 3: Policy recommendations

Category	Maxwell et al. 2011	Van den Bergh 2011	Santarius 2012	Semmling et al. 2016	Vivanco et al. 2016
policy design	Design, evaluation and performance of policy instruments			Policy design Policy mix	Policy design (recognition in policy design, broader definitions and toolkits, benchmarking tools)
regulatory instruments		Command-and-control	Efficiency standards Absolute caps	Efficiency standards	
market-based instruments	Economic instruments	Subsidies Price regulation Tradeable permits	Ecotaxes	cap and trade Subsidies and financial support Tradeable Permits Taxes and fees	Environmental economic policy (energy/carbon tax, bonus-malus schemes, cap and trade schemes, rebates and subsidies)
soft instruments	Sustainable lifestyles and consumer behavior Technology and innovation Awareness rising and education in business New business models	Information provision and “moral suasion”	Sustainability communication	Information and communication instruments (feedback on absolute consumption, consumer trainings and campaigns, labelling) Default standards / nudging Voluntary agreements	Sustainable consumption and behavior (consumer information, identity signaling, standardisation, autonomous frugal behavior) Innovation (targeted eco-innovation) New business models (product service systems)

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