Conceptual framework for exploring company-level rebound effects

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1. Introduction

Production and consumption are associated with energy and material use and place an unprecedented burden on the functioning of ecosystems that are fundamental to humanity (Rockström et al. 2009; Steffens et al. 2015). Therefore, an absolute reduction of energy and material consumption (in short: resource consumption) is necessary. Until now, the slogan has been: Increase resource efficiency in production and consumption. Increasing the resource efficiency of products and services in all phases of their life cycle should reduce the absolute consumption of resources and the associated environmental impact. After years of implementation, substantial resource efficiency improvements can be observed in numerous areas; this applies to both the manufacturing of products and their use. So far, however, these efficiency improvements have not been sufficient to reduce resource consumption to the extent necessary for sustainable development (UBA 2021; Destatis 2021). The academic literature has identified the rebound effect as one of the reasons why higher resource efficiency is not accompanied by an equal reduction in resource consumption.

Rebound effects occur when successful efficiency improvements lead to changes in behavior that (partially) offset the expected savings. As a result, the environmental benefits are lower than expected on the basis of the efficiency increase and theoretically possible (Hertwich 2005; Sorrell 2009). Rebound and similar effects can therefore also be seen as impact deficits of resource efficiency measures. Rebound effects arise, among other things, because increases in energy or material efficiency in companies increase the productivity of companies, which allows expansion of production and sales (Saunders 1992; Santarius 2015; 2016). In addition, the (often) price-reducing effect of resource efficiency improvements can stimulate additional consumption, which in turn can trigger higher-than-expected resource use in firms and households (Khazzoom 1978; Sorrell 2007; Jenkins et al. 2011).

In the following, we shed light on the phenomenon of the rebound effect at the company level. So far, rebound effects have mainly been studied using economic methods on the consumption side (Sorrell 2007; Santarius 2015). Investigations on the production side have mostly been done at a higher aggregate meso or macro level of industries, sectors, or the economy as a whole (e.g., Lange et al. 2021; Lutz et al. 2021; Font Vivanco et al. 2014; Chakravarty et al. 2013; Van den Bergh 2011; Antal & van den Bergh 2014). In contrast, we conceptualize rebound effects at the firm level in this paper. Our research questions are thus exploratory in nature and are:

- Which types of company-related rebound effects can be distinguished?
- In the context of which processes do company-related rebound effects arise?
- Why (through which drivers) do company-related rebound effects arise?

We assume that the emergence of rebound effects is directly related to decisions and activities during or after the successful implementation of efficiency measures. A better understanding of the role of these decisions and activities seems necessary to understand the rebound effect, defined as the difference between theoretically possible and actual savings through efficiency improvements.

In **Chapter 2**, after a brief description and definition of the rebound effect, we prepare the central findings of the existing scientific literature on company-related rebound effects. Different typologies of rebound effects in the research literature are presented.

Chapter 3 provides an overview of the concept developed in the research project "Comprehensive Management of Energy and Resource Efficiency in Enterprises" (MERU) to describe and explain enterprise-related rebound effects. First, rebound effects are distinguished from other implementation and impact deficits of efficiency strategies in order to better understand the counterintuitive impact of efficiency improvements on absolute resource consumption. Subsequently, the basic understanding of the emergence of company-related rebound effects as a process in the course of and after a successfully implemented efficiency increase is presented. Rebound effects are conceptualized with the help of a schematic chain of effects between a successful efficiency increase, the subsequent behavioral changes (i.e. decisions and activities in the company) and their consequences for energy and material resource consumption.

We identify specific characteristics of efficiency measures as the starting point for the emergence of rebound effects. We describe the financial, ecological and technological advantages pursued with an increase in efficiency as triggers of possible rebound effects. Finally, we summarize the considerations in a detailed process model. Starting from an efficiency increase, it leads via behavioral changes in the company to a typology of company-related rebound effects.

Rebound effects are the result of different rebound mechanisms (cf. Lange et al 2021), which can explain the ecological impact deficits of efficiency improvements. The developed rebound process model and the associated rebound typology thus provide a comprehensive conceptual framework for rebound effects at the company level. With the help of this conceptualization, it is possible to outline how and why absolute resource consumption in the wake of efficiency improvements can turn out to be higher than what would be assumed on the basis of an isolated consideration of the efficiency improvement alone. With the help of this understanding, it is also possible to identify possible courses of action for reducing the impact deficits at the company level.

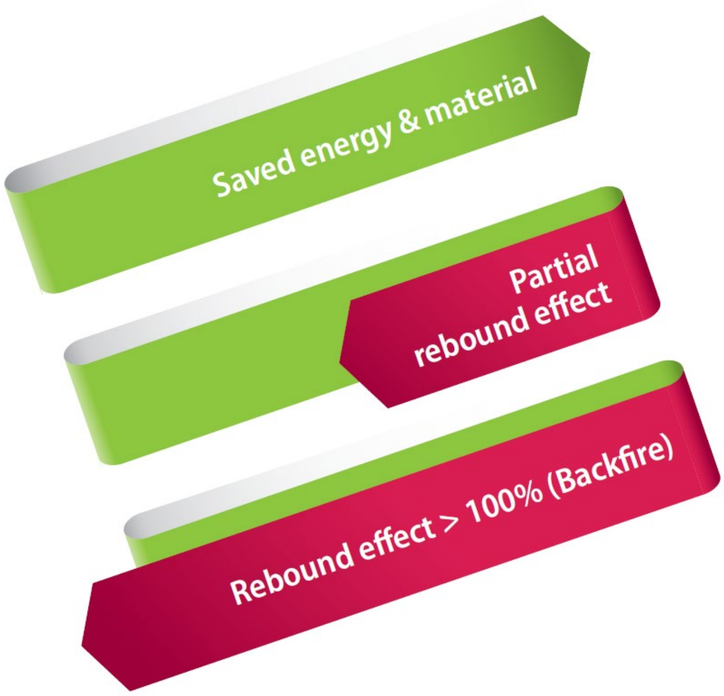
Chapter 4 draws conclusions. Despite rebound effects, corporate efficiency efforts make sense and are necessary to reduce the ecological problem pressure. However, it is important that companies and policymakers become more aware that efficiency measures often do not generate the savings that are theoretically possible. In companies, targeted efforts at the strategic and operational levels, as well as the involvement of employees, can help not only to reduce the impact deficits of efficiency measures, but also to positively reinforce efficiency measures (reinforcement effect).

2. State of research on rebound effects

Rebound effects can **occur during or after the successful implementation of efficiency measures** as a result of behavioral adaptations. They reduce the hypothetically possible expected reduction in absolute resource consumption through the increase in efficiency. If measures to increase energy or material efficiency should (also) reduce ecological impact, rebound effects form a specific form of **impact deficit** of these efficiency measures. These **behavioral changes** can partially or completely cancel out the reduction of energy/resource consumption and the accompanying environmental impact of the efficiency measure and, in extreme cases, lead to additional burdens (cf. Hertwich 2005). Behavioral changes refer both to unconscious or non-reflective reactions to efficiency improvements, and to conscious, well-considered decisions and activities with which the advantages of efficiency improvements in production and consumption are exploited.

The basic mechanism of the rebound effect was described early on in the 1860s by William Stanley Jevons in connection with efficiency improvements in coal combustion in steam engines (Jevons [1865]; 2001): Counterintuitively, James Watt's substantial increase in the efficiency of the steam engine – a six-fold increase in the energy yield from the same amount of coal compared to the processes previously used in steam engines – had not led to savings in the overall consumption of coal. Rather, it significantly favoured the use of coal as an energy resource and, over time, led to more and more applications of the steam engine in various industries. As a result, a larger absolute amount of coal was consumed after the coal-saving efficiency increase than before (this is called the **“Jevons’ Paradox”**, named after the first observer of the effect). This initial example also forms a special case of the rebound effect, the so-called **“backfire effect”** (see figure 1). In this case, the increase in efficiency is followed by an absolute increase in the consumption of resources.

Figure 1: Schematic presentation of the rebound effect



Source: Wolff et al. (2023).

The counterintuitive and sometimes counterproductive effect of some efficiency improvements has thus been known for a long time. However, the phenomenon was only revisited in the late **1970s** and studied in the context of **household energy use** (Khazzoom 1980). Later, it was identified as a potential problem for the effective reduction of greenhouse gas emissions, provided that these are based on energy efficiency measures only (Brookes 1990). The concept of the rebound effect has mostly been related to energy consumption (i.e., electric power or fuel). It has only rarely been applied to the consumption of other resources or materials (Berbel et al. 2015, 2018; Meyer et al. 2007; Meyer et al. 2012; Pfaff & Sartorius 2015; Schmidt et al. 2019; Chen 2021).

Also in recent years, the rebound effect has mainly been researched on the **consumption side** with regard to the use of more (energy) efficient products by households (Greening et al. 2000; Sorrell 2007; Jenkins et al. 2011; Santarius 2015). Companies are only indirectly considered here through the development and provision of these products. The problem of rebound effects has thus been located primarily in consumption among households, although its historical roots are on the **production side**. Jevons also originally argued for a much greater relevance of the effect on the production side due to the level of consumption and existing incentives to expand the use of resources (Jevons [1865]; 2001: 99).

The **extent of the rebound effect** is usually expressed as a percentage value describing the ratio between theoretically possible savings expected on the basis of the efficiency improvement (without behavioral changes) and actual savings. For example, a rebound effect of 30 % means that 70 % of the savings are realized and the remaining 30 % are eaten up by changes and adjustments in behavior. In the extreme case of the “back-fire” effect already mentioned and visualized in Figure 1 above, resource consumption after an efficiency increase is counterintuitively higher than before and thus constitutes a rebound effect of more than 100 % (cf. Sorrell 2007; 2009). From an ecological perspective, these types of efficiency measures are counter-productive, since after the successful efficiency increase, higher resource consumption occurs than before the efficiency increase.

However, the occurrence of rebound effects by no means renders efficiency-enhancing measures for ecological protection superfluous: Except in the (exceptional and extreme) case of a backfire, efficiency measures still result in resource savings despite the occurrence of rebound effects. The backfire effect, however, has hardly been proven so far, although it cannot be ruled out in principle (Sorrell 2009). The existence of rebound effects should therefore not be misunderstood as a reason to regard efficiency efforts as useless. Rather, the question is how efficiency measures can be implemented in companies as ecologically effectively as possible and how they can be integrated into the comprehensive management of energy and material efficiency.

2.1. Existing typologies of rebound effects

In the context of research, different types of rebound effects are described. So far, a distinction has been made primarily between rebound effects at different levels of analysis (micro, meso, macro), between direct and indirect rebound effects, and between different sources.

With regard to the **level of analysis** – specifically: the economic **micro, (partly meso) and macro levels** – studies of the purchasing and usage behavior of households at the micro level have dominated the literature to date (Santarius 2015). Over time, the study has expanded from industry- and sector-level rebound effects in the context of production to the countervailing effects of higher energy efficiency at the macro level of entire economies (Jenkins et al. 2011; Santarius 2015; Lange et al. 2021). In each case, the expected savings from efficiency improvements are compared to actual resource consumption at the respective levels of analysis. Rebound effects are thus to be understood as multi-level phenomena. Due to the many interactions (amplifications, but also cancellations) between the individual levels, they cannot simply be added up as a total, but should be determined specifically for each level of analysis (Sorrell 2007; Lange et al. 2021).

In addition to the level of analysis, the scientific literature distinguishes between **direct** and **indirect rebound effects**. The basis of this distinction is the immediateness of the connection between the increase in efficiency and the higher-than-expected resource consumption (characterizing the rebound effect). In the case of direct rebound effects, the higher-than-expected consumption results from the fact that a more efficient process or product is used differently than before. For example, a more efficient car that consumes less fuel can be driven longer distances at the same cost, so that ultimately less or no fuel is saved. The mapping between efficiency gains and impact deficits is comparatively simple here. In the case of indirect effects, the original efficiency improvement is a cause or enabling condition for effects elsewhere, which can only come into play under certain circumstances. This is the case, for example, when financial savings from the fuel-efficient car are not (or not only) used for further journeys or more frequent trips, but are spent on consumption elsewhere, thus triggering further resource consumption. In order to be able to classify an impact deficit as an indirect rebound effect, a causal link must therefore be established between the increase in efficiency and the higher-than-expected resource consumption.

Rebound effects are also frequently categorized according to the **cause** of the impact deficit and thus according to the origin of the higher-than-expected resource consumption. In the area of consumption, these primarily include income and substitution effects. In the case of i**ncome effects**, the increase in efficiency leads to higher disposable income, which is used for more frequent purchases or more intensive use of the same product (or other products or services) and can thus lead to additional resource consumption. In the case of the **substitution effect**, a less efficient product is replaced by one that is more efficient and thus becomes financially affordable to use (for example, the cash savings from an efficient three-liter car may lead someone to stop taking the train because they can now afford to drive, Santarius 2015). Energy intensity and total energy consumption of consumption increase because less energy-intensive consumer goods are replaced by goods that are inherently more energy-intensive but are now more affordable because of the increase in efficiency (Khazzoom 1980; Jenkins et al. 2011).

On the production side, output and factor substitution effects have been primarily discussed so far. In the case of **output effects**, higher than previously expected resource consumption occurs when production and sales figures increase as a result of cost- and price-reducing efficiency improvements. In the case of **factor substitution effects**, the energy or material intensity of production processes increases when human labor is replaced by the comparatively more efficient energy and material services provided by machines (Saunders 1992; 2014; Jenkins et al. 2011; Santarius 2015; 2016).

Less frequently and rather only conceptually, higher-than-expected resource consumption and rebound effects are dealt with through the “re-investment” of released financial resources, through “re-design” or “embodied energy”. **Re-investment** is the use of financial resources that were saved by increasing efficiency and that are now used, for example, to diversify the product portfolio, which in turn is associated with resource consumption. The "**re-design**" effect refers to changes in product design that (proportionately) offset potential consumption reductions through higher performance (Santarius 2016). Under the term **"embodied energy"**, some authors classify the energy required to provide or carry out the efficiency improvement as a rebound effect (Jenkins et al. 2011; Santarius 2016).

In the discussion, **other types of effects** are mentioned sporadically, such as (1) general secondary effects, i.e., more distant consequences of efficiency gains (e.g., price adjustments in commodity markets) that (partially) erode original savings. (2) transformational effects, which include qualitative and structural changes in consumption patterns, (3) frontier effects, which describe the development of novel product categories and entire industries, or (4) thermodynamic effects, in which efficiency gains are directly translated into higher output (Galvin 2020). In all of these effects, savings as a result of efficiency improvements (alone or in combination) may be mitigated by more distant, higher-than-expected resource consumptions. However, changes in the use of more resource-efficient technologies are often difficult to attribute to the efficiency improvements themselves.

2.2. Existing explanations of the rebound effect

So far, the literature mainly focuses on four (types of) causes of rebound effects: economic, technical, psychological and social.

The focus of the discussion is on the **economic causes**, i.e. on the financial savings resulting from efficiency improvements. As mentioned above, higher resource efficiency and thus lower consumption often result in lower costs for consumers, who can expand their consumption as a result. In companies, financial savings as a result of increased efficiency enable price reductions or higher margins. These financial resources can be used for other purposes and goals of the company and in turn trigger new resource consumption (Khazzoom 1978; Saunders 1992; Santarius 2015).

In addition, some authors also list **technical** causes. So far, the focus here has been on the fact that resources are required to bring about and implement the efficiency increase; the focus is mostly on embodied energy (or "gray energy") (Jenkins et al. 2011; Santarius 2015; 2016). However, some authors explicitly do not classify resource consumption of gray energy as a rebound effect (Friedrichsmeier & Matthies 2015; Font Vivanco et al. 2016). The reason is that gray energy consumption does not occur after the implementation of an efficiency measure but is directly linked to its introduction or even precedes its introduction. This type of effect therefore does not correspond to the definition of rebound effects given at the beginning; it is therefore also excluded from further consideration (cf. chapter 3.1). Nevertheless, technical causes of rebound effects are conceivable as efficiency-based performance increases, which can lead to changes in behavior during or after the increase in efficiency. Examples are discussed in chapter 3.2.2 under the term "technological advantages" of efficiency increases.

The literature also discusses possible **psychological** causes of rebound effects (Santarius 2015; Santarius & Soland 2018). After an increase in efficiency of products and services, their environmental compatibility can be re-evaluated by users. This reassessment may result in behavioral changes that are associated with higher-than-expected resource consumption. In this case, the ecologically beneficial increase in efficiency itself is the reason for a change in preference and behavior by consumers (whereas in the economic or financial explanation of rebound effects, it is assumed that the preferences of the actors remain the same and that a higher budget is available for use).

Finally, routines and everyday practices are considered possible **social** causes of rebound effects (Winther & Wilhite 2015; Galvin & Gubernat 2016; Sonnberger & Gross 2018). These include, for example, comfort-oriented heating routines in the face of more efficient technologies or the adaptation of user behavior to (perceived) technical requirements and infrastructures. For example, heat pump-heated homes often allow air circulation instead of closing doors to less heated rooms (Winther & Wilhite 2015).

2.3. Findings on the size of the rebound effect

The occurrence of rebound effects is almost undisputed in the scientific discussion: The assessment is shared that resource efficiency increases are often accompanied by lower costs and price reductions, which lead to quantity adjustments in consumption when demand is not saturated. In contrast, the magnitude of rebound effects and their savings-consuming impact is highly contested in the literature (Sorrell 2009; Sorrell et al. 2009; Gillingham et al. 2013). On the **consumption** side, review studies show that the magnitudes of rebound effects due to behavioral changes converge in different areas of consumption. Mainly rebound effects of private mobility behavior have been investigated (10-30 %), heating of residential spaces (10-30 %) as well as their cooling (1-26 %) (Jenkins et al. 2011, 15).

In contrast, microeconomic research on rebound effects on the **production** side shows drastically different results. In the context of the studies, which have mostly dealt with different areas of the economy at the **industry or sector level**, the focus has so far been on energy in production processes in light and heavy industry as well as fuel consumption in the transportation of goods. The size of the rebound effects identified there ranges from relatively small increases in savings to a multiple backfire of potential savings. Depending on the study context and time period, the results vary widely. For example, according to the studies, only 4 % of savings in EU15-wide goods transportation are eroded in the period between 1995 and 2012 (Llorca & Jamasb 2017), while in heavy industry in China, consumption more than tripled after efficiency improvements, with a rebound effect of 334 % (Li and Lin 2017). An overview of empirical studies is provided in Table 1 (below). A general trend and converging estimates as in areas of consumption are not apparent. It can only be noted that higher rebound effects tend to be recorded in studies that have chosen China – i.e. a growth region – as a geographical region with observation periods between the 1980s and 2010s.

Table 1: Empirical findings on the size of rebound effects in different industries, countries and time periods

Autor(s)	Year	Country	Sector	Resource	Time Period	Size of rebound effects
Bentzen	2004	US	Manufacturing	Energy	1949-1999	24,00 %
Matos & Silva	2011	PT	Road freight transport	Fuel consumption	1987-2006	24,10 %
De Borger & Mulalic	2012	DK	Road freight transport	Fuel consumption	1980-2007	10 % in short term, 17 % in long-term
Evans & Schäfer	2013	US	Air traffic	Fuel consumption		16-21 %
Lin & Li	2014	CN	Heavy industry	Energy	1980-2011	74,30 %
Wang & Lu	2014	CN	Road freight transport	Fuel consumption	1999-2011	super conservation nation -9 % eastern -11 % central -29 % and western -13 %
Lin & Xie	2015	CN	Food industry	Energy	1980-2012	34,39 %
Li et al.	2016	CN	Aggregate 36 industrial sectors	Energy	1998-2011	88,42 %
Lin & Tian	2016	CN	Light industry	Energy	1980-2012	37,70 %
Lin & Zhao	2016	CN	Textile industry	Energy	1990-2012	20,99 %
Zhang et al.	2017	CN	Aggregate industry	Energy	1995-2012	39,00 %
Du et al.	2017	CN	Construction	Electricity	1990-2014	59,50 %
Lin & Tan	2017	CN	Energy intensive industries	Energy	2006-2012	90,75 %
Li & Lin	2017	CN	Heavy industry	Energy	1994-2012	334,30 %
Li & Lin	2017	CN	Light industry	Energy	1994-2012	189,70 %
Zhang et al.	2017	CN	Manufacturing	Energy	1995-2012	28,00 %
Lin et al.	2017	CN	Nonferrous metals industry	Energy	1986-2014	83,02 %
Yang & Li	2017	CN	Power generation	Fossil-energy consumption	1985-2010	11,60 %
Llorca & Jamasb	2017	15 EU countries	Road freight transport	Fuel consumption	1992-2012	3,8 % (high variations between countries, e.g. DK with 66,8 %)
Ruzzenenti & Basosi	2017	EU	Road freight transport	Energy	1998-2007	-74,00 %
Ruzzenenti & Basosi	2017	EU	Road freight transport	Energy	1998-2011	-146,00 %

Ruzzenenti & Basosi	2017	EU	Road freight transport	Energy	1998-2007	
Ruzzenenti & Basosi	2017	EU	Road freight transport	Energy	1998-2011	
Song et al.	2018	CN	Agricultural sector	Water	1998-2014	61,49 %
Amjadi et al.	2018	SE	Chemical	Fuel consumption	2000-2008	62,00 %
Amjadi et al.	2018	SE	Chemical	Electricity	2000-2008	76,00 %
Ouyang et al.	2018	CN[1]	Industrial sectors of that region	Energy	2003-2013	40,04 %
Amjadi et al.	2018	SE	Iron and Steel	Fuel consumption	2000-2008	65,00 %
Amjadi et al.	2018	SE	Iron and Steel	Electricity	2000-2008	86,00 %
Wang et al.	2018	CN	Iron and Steel	Energy	1985-2015	73,88 % on average
Amjadi et al.	2018	SE	Mining	Fuel consumption	2000-2008	58,00 %
Amjadi et al.	2018	SE	Mining	Electricity	2000-2008	82,00 %
Amjadi et al.	2018	SE	Pulp and paper	Fuel consumption	2000-2008	64,00 %
Amjadi et al.	2018	SE	Pulp and paper	Electricity	2000-2008	84,00 %
Sorrell & Stapleton	2018	UK	Road freight transport		1970-2014	49-61 %, 21-137 %
Li et al.	2019	CN	Industry sectors in analysed regions	Energy	1996-2015	66,70 % - 112,31 % depending on region and time period
Li et al.	2020	CN	Industry (general)	Energy	2006-2015	36 % (nation-wide), 38 % (East), 41 % (Central), 30 % (West)
Wei et al.	2020	CN	Energy intensive industries	Coal	1990-2016	35,07 %
Bruns et al.	2021	US	Industry (general)	Energy	1992-2016; 1973-2016[2]	Circa 100 %
Berner et al.	2022	DE	Manufacturing	Energy	2003-2014	4,50 % bis 5,30 %
Lin & Zhu	2022	CN	Mining	Energy	2012-2016	46,40 %
Zheng et al.	2022	CN	Transport	Energy	2003-2017	82 % (shor-term) to 123 % (long-term)

Sources: diverse (see left column), own collation (chronological, alphabetical).

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[1] Yangtze River Delta urban agglomeration.

[2] 1992-2016 (Jahresdaten), 1973-2016 (Quartalsdaten)

With regard to the size of the rebound effect described in studies to date, however, it should be noted that, with a few exceptions, these studies mostly examine **direct effects** only and thus do not consider indirect effects that are more distant in space and time. Thus, the size of the overall effect is likely systematically underestimated due to the study design (Dimitropoulos 2007; Barker et al. 2009). Macroeconomic studies on rebound effects at the level of **national economies** find an average deficit of 50 % of the hypothetically possible savings (Brockway et al. 2021).

2.4. Conclusion

Many years of research on rebound effects show that relative savings in resource consumption do not necessarily lead to proportionally decreasing absolute consumption of these resources. Recently, rebound effects have been increasingly discussed as a problem for effective contributions of efficiency improvements to environmental protection. Rebound effects cause that the environmental impact of resource efficiency improvements is lower than expected. This applies not only to energy consumption in the form of fuel and electricity, but also to the use of other resources such as water, land and materials.

The emergence of rebound effects is particularly problematic if – as is often the case – it is assumed that efficiency improvements translate proportionally into absolute reductions in consumption, and are thus assessed in full for ecological protection (cf. Brockway et al. 2021 on the scenarios and assumptions of CO2 projections and modeling of entire economies, in which forecast efficiency improvements are dealt with in this way). However, depending on the magnitude of the rebound effects that actually occur, even greater efforts may be needed, as the assumed effects of the measures and those assumed in model calculations cannot be realized to the estimated extent in view of rebounds. Further measures would be necessary to compensate for these effect deficits and to lead to the necessary ecological protection.

Empirical research still focuses on studying rebound effects on the consumption side of private households. Recently, however, more attention has been paid to the rebound effect on the side of production and provision of services. This is important, among other things, because far-reaching decisions are also made for consumption by households through the design of the supply of products and services. At the same time, there is no limit to resource consumption on the production side analogous to the saturation of demand. Currently, research on the production side is still dominated by macroeconomic methods, which examine the business in a relatively abstract way and thus inadequately capture the reality of operational decisions and activities as behavioral changes and the origin of rebound effects. In the following, we therefore develop a conceptual framework that is more strongly oriented towards the processes and decisions of companies.

3. The MERU concept: delimitation, typology and explanation of company-related rebound effects

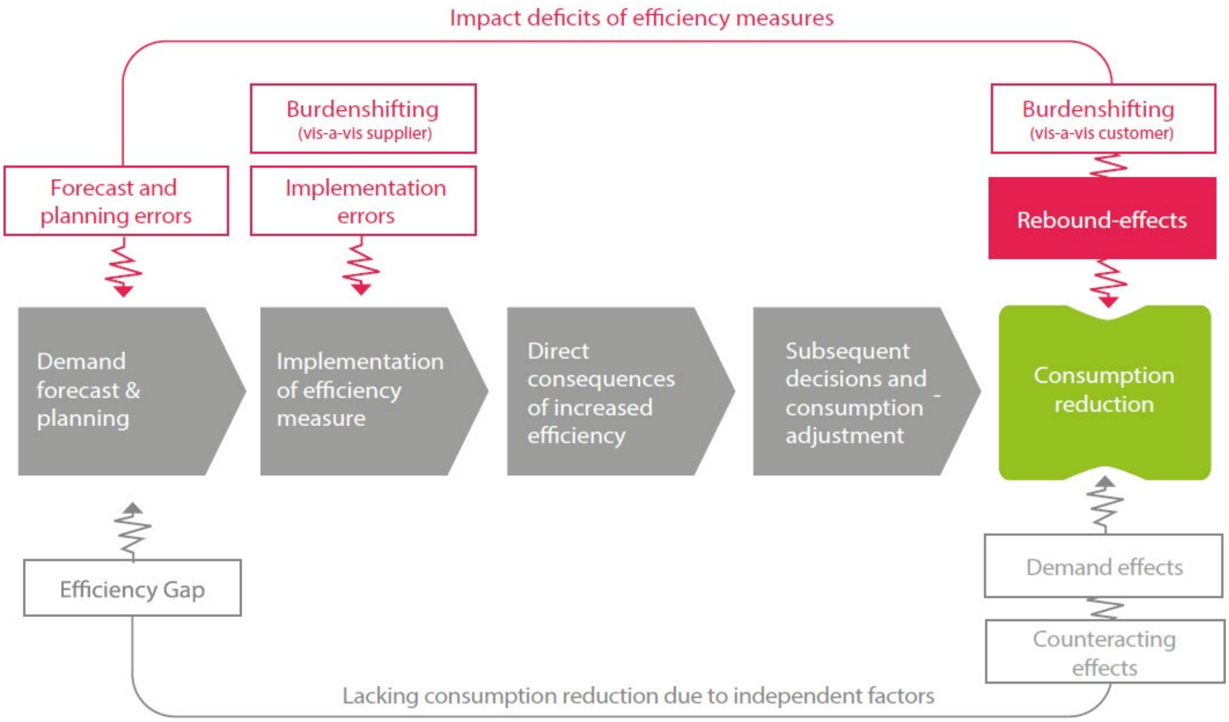
The aim of the ("MERU") approach developed here is to relate the concept of the rebound effect more strongly to what happens in companies. To contribute to a better understanding of company-related rebound effects, we will put the role of corporate decisions and activities at the center of our approach. A better understanding of the origin of rebound effects can help companies to identify options for action that can reduce or avoid rebound effects.

Before we try to explain the emergence of rebound effects with the help of a process model (Chapter 3.2) on the one hand and with the help of propositions (Chapter 3.3) on the other, we first distinguish rebound effects from other impact deficits of corporate efficiency measures (Chapter 3.1). In this way, we attempt to give more structure to the sometimes-diffuse debate in rebound discussions.

3.1. Rebound effects as specific impact deficits of efficiency measures

In the context of sustainable development, energy and material efficiency measures should reduce the absolute consumption of energy and materials to reduce pressure on the ecological environment. Rebound effects describe the phenomenon that – as shown at the beginning – the theoretically possible and expected reductions are often not realized or not realized to the full extent. Rebound effects are thus a specific impact deficit of efficiency efforts. In addition to rebound effects, there are other effects that can limit the impact of efficiency measures and strategies. The cause of the lower-than-expected reduction in consumption may be causally linked to the efficiency measure (in which case we speak of "impact deficits") or it may be independent of it (in which case we speak of "counteracting effects").

Figure 2: Impact deficits related to efficiency measures



Quelle: Wolff et al. (2023).

Impact deficits can occur before, during, or after an efficiency measure:

- **Forecasting and planning errors as well as implementation problems:** Difficulties such as incorrect forecasts, planning errors, implementation problems or operating errors occur before or during the implementation of efficiency measures and result in efficiency potentials not being fully exploited. These factors can be eliminated with better forecasts and planning, in the course of implementation or afterwards, in order to achieve the targeted or expected increase in efficiency.
- **“Burden shifting”:** The implementation of the efficiency measure leads to additional consumption in other environmental media or in other life cycle phases of a product (i.e. in the upstream or downstream value chain). This also includes resource consumption, which in the literature and in practice is usually referred to as the (ecological) “backpack” and is necessary in the form of “embodied energy” and “gray material” to achieve and bring about the efficiency improvement. Gray energy and gray material are partly categorized as rebound effects by a few authors (see chapter 2.2). However, such shifts in consumption can be known in principle if the measure is carefully examined (e.g. with the aid of life cycle analyses/LCAs) (cf. Friedrichsmeier & Matthies 2015; Font Vivanco et al. 2016) and are not triggered by behavioral changes in the course of efficiency improvement.
- **Rebound effects**: A successful efficiency measure leads to changes in behavior and/or other adjustments in the course of its implementation or afterwards, which trigger new resource consumption. The consumption reductions that would have been theoretically possible with the efficiency measure are therefore not fully achieved. “Theoretically possible” reductions are expected savings: It is often implicitly or explicitly expected that these can be converted 1:1 into lower consumption. In turn, the rebound effect is a collective term for the consequences for resource consumption of different (rebound) mechanisms that lead to these economic deficits (Sorrell 2009; Lange et al. 2021; see also Chapter 3.4).

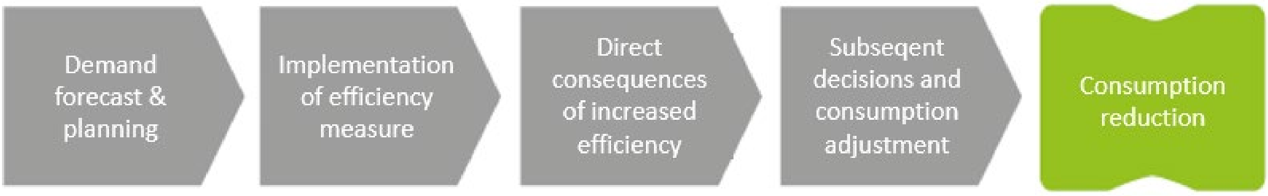
Countervailing effects are causally independent of an efficiency measure, but also reduce its impact or, in extreme cases, prevent it from occurring:

- **Efficiency Gaps:** In this case, measures to increase efficiency are not even implemented, even though they would make sense both economically and ecologically. The reasons for this can be structural and include, for example, distorted energy prices, uncertainty about their future development and a lack of capital resources for the necessary investments. Political and regulatory framework conditions, attitudes of decision-makers towards energy efficiency and risk perception with regard to the necessary investment, a lack of information and misaligned incentives can also play a role (Hirst & Brown 1990; cf. Jaffe & Staffins 1994 with an alternative breakdown according to market and non-market failures in this context).
- **Demand effects:** Irrespective of an increase in efficiency, the demand for a product rises and, with demand and output in the company, the resource requirements for its production.
- **Other counteracting side effects:** Independently of an increase in efficiency, resource requirements for processes/products increase due to external requirements (for safety, environmental protection, etc.). One example is the increasing requirements from new technical instructions for keeping the air clean, which can lead to a reduction in potential energy savings.

3.2. The emergence of rebound effects as a process

As described, rebound effects arise by definition after successfully implemented efficiency measures, if the efficiency measure itself leads to behavioral changes (decisions, activities) that reduce the actual resource savings compared to the theoretically possible savings (cf. Hertwich 2005). To make this phenomenon more tangible, we conceptualize the successful implementation of an efficiency measure and its direct and indirect consequences for resource consumptions – more explicitly than the literature has done so far in its definitions and typologies – as a process with several steps, which we relate to what happens in the company. This analytic decomposition into four steps can help decision-makers in companies to better understand the emergence of rebound effects and the role of their own actions and to develop strategies to reduce the problem.

Figure 3: Emergence of rebound effects as a process – basic logic



Source: Wolff et al. (2023).

The **first step** in the emergence of the rebound effect is the planning of a measure to increase the resource efficiency of a product or process in the company. This usually involves estimating or forecasting future demand and usage patterns.

In the second step, the measure is implemented. As a rule, the objective of the efficiency measure is to achieve financial, ecological and/or technological advantages. These advantages – as specific goals of the efficiency increase – are more or less closely related to the other goals of the company (increase in sales, expansion of the product portfolio, etc.).

The efficiency measure can be characterized by its specific objectives, i.e. how much in terms of costs or resources (materials and energy) is to be saved, how much more efficient can/should the product or process become as a result of the efficiency improvement? Based on these specific targets for saving resources, the theoretically possible savings then result as a basis of comparison for the rebound effect.

In the **third step**, **which follows the efficiency measure**, the financial, environmental and/or technological benefits of the efficiency improvement arise after its successful implementation. These direct consequences can be identified as causes for decisions and activities as behavioral changes in the company, which in the further course – depending on how the company uses the various benefits – can lead to rebound effects.

In the subsequent **fourth step**, decisions, activities and other behavioral changes take place within the company during or after the efficiency improvement (e.g., changed asset utilization, financial decisions), which exploit the cost-reducing or performance-enhancing benefits of the efficiency improvements. The resulting changes in core and support processes may not only affect resource consumption within the company but may also have consequences for resource consumption within the supply chain, in sales markets, and in consumer use.

In the **fifth step,** the consequences of these decisions and activities within the company – and possibly beyond (supply chain, sales markets, customers) – for the level of resource consumption can be identified. Only now is it possible to assess, on the basis of the actual savings and the link to the behavioral changes, whether any impact deficits can be classified as rebound effects.

The benefits targeted by the efficiency measure play a decisive role in determining the further process of the emergence of rebound effects and are therefore examined in more detail below. Chapter 3.5 then explains the two further process steps that lead to rebound effects via the utilization of the financial and technological benefits of efficiency enhancements.

3.2.1. Understanding efficiency as a frame of reference for the rebound effect

The starting point for the development and thus also for the investigation of the rebound effect is formed by efficiency measures that reduce the energy or material input per output or service unit in the company and thus increase its resource efficiency. The understanding of the output or service unit is central to the definition of the efficiency concept applied in each case and thus also to the understanding of the rebound effect that may arise.

The economic-ecological measure of **efficiency** is the ratio between a resource input and a service output. In the case of resource input, a distinction can be made between energy resources (energy efficiency) and material resources (material efficiency).

From an ecological perspective, it is crucial that different quantities and qualities of energy and material inputs imply different quantities and qualities of environmental impact. In the case of service output, different horizons of observation can be applied, which thus have far-reaching implications for the understanding of efficiency: The service can be ...

- concerned with the manufactured product (product efficiency)
- specific functions that this product should fulfill (functional efficiency)
- or a need of the consumer that the service should help to satisfy (need efficiency).

In this context, the efficiency of a product, function or need fulfillment is formally summarized as the equation $\frac{service}{resources} = \frac{product \rightarrow function \rightarrow need}{energy/material}$. This equation should be further specified in terms of resource inputs and service outputs, depending on the application under consideration, in order to obtain a common understanding of the concept of efficiency and thus of efficiency improvement. An increase in efficiency is the precondition for the possible occurrence of a rebound effect. In formal terms, **efficiency improvement** consists of a change in the ratio between resource inputs and services as outputs, which can be used either to increase output a) $\frac{more\ service}{same\ resources}$ or to reduce input b) $\frac{same\ service}{less\ resources}$

The planning and implementation of an **efficiency measure** is in turn the precondition for an increase in efficiency in a company – and thus the starting point for addressing rebound effects in companies.

3.2.2. Efficiency measures and their rebound-relevant properties

In addition to this basic understanding of efficiency, the understanding of an efficiency measure is of importance, which is likely to play a central role in the subsequent evaluation of the ecological effectiveness of a specific measure. In the following, the focus is on the objectives and characteristics of the efficiency measures, as well as the benefits they aim to achieve, which are relevant for the behavior of the actors in companies and can therefore be considered as causes of the rebound effect. In order to distinguish other implementation and impact deficits from the rebound effect, the successful implementation of an efficiency measure is initially important, as described above. Ideally, other impact deficits that arise due to incomplete or inadequate implementation of an efficiency measure can already be identified here. By definition, the rebound effect only occurs after the successful realization of an efficiency improvement; in principle, the following applies: Without an efficiency improvement, there is no rebound effect.

Among the rebound-relevant characteristics of efficiency measures, **their goals and intended benefits**, the **mode of action of the efficiency improvement**, and their **financial and material requirements** can be identified.

Efficiency improvement can be identified as **bringing about financial, environmental and technological benefits**. In addition to the **environmental benefits** of lower energy and material use, other benefits of a financial and technological nature arise from the input-side cost-reducing and output-side performance-enhancing effects of efficiency improvement. **Financial benefits** arise because lower resource use per unit is often accompanied by lower costs for companies and their customers or is the primary objective for their implementation (Saunders 1992). Because of the reduced resource use, the cost (and derived price) of producing or acquiring and using the product or service improved by the efficiency improvement decreases. If lower costs are not passed on to customers as price reductions, the higher margins can generate higher profits over time, which can subsequently be used for other purposes in the company and thus trigger further resource consumption (Santarius 2015).

In addition to financial benefits, various **technological advantages** are achieved through efficiency gains. With an equally high (or lower) input of resources, performance- and benefit-enhancing changes can be made to existing products and services (e.g. by increasing performance, comfort, safety) (Santarius 2016) or by enabling the development of completely new products and technologies (Jenkins et al. 2011). This performance-enhancing effect can also occur analogously in processes within companies or be explicitly targeted when efficiency improvements are implemented, for example, for improvements in indoor air or ventilation quality.

With regard to the **impact of the efficiency measure**, the question is how resources are saved and where in the value chain the measure has its effect. A selection of numerous starting points and possibilities for increasing efficiency is shown in Table 2.

Table 2: Rebound-relevant characteristics of efficiency measures

Goals of efficiency measure	**What is the motivation for the measure? What benefits are to be achieved through the increase in efficiency?**	• Achieving financial and technological benefits to increase output, save costs, improve quality, increase performance, etc. • Achieving financial, environmental and technological benefits • Achievement of ecological benefits for environmental protection is in the foreground, financial aspects play a subordinate role • Other motives and goals, in many different mixed forms …
	How high is the intended increase in efficiency?	• Size of intended efficiency improvement in physical and financial terms

		• Isolated effect of the measure per immediate, as reduction of resource consumption per unit, per process or per time unit (also in relation to the total consumption)
Impact mechanism of efficiency measure	**How are resources saved? In what way does the measure develop its effect?**	• Starting point of the efficiency measure ○ Product, process or organizational change • Specific effect of the efficiency measure ○ Change in material selection, changes in product design (less material and energy "in" the product), lightweight and compact construction. ○ o Use of energy-saving processes, automation and control, recycling of materials ○ o Changes in work processes, choice of more efficient service offerings, etc. • In-house development or procurement/purchasing from other organizations?
	Where in the value chain is the efficiency measure located?	• Composition of the product (product design) • Primary value creation processes: Core processes in production and provision of services • Supporting processes in the company (lighting, cooling, heating ...) • In the company or in the supply chain
Financial and material requirements of the efficiency measure	**Does the measure require an investment?**	• Amount and type of investment (expansion or replacement investment) • Amortisation period
	What technical and material requirements are associated with the measure?	• Acquisition of new plants, assemblies and equipment for efficiency improvement • Level of resource consumption in the supply chain compared to the savings achieved in the company

Source: own.

For a comprehensive view of the impact on resource consumption, the **financial and material requirements** (i.e. investments, gray energy/materials) of an efficiency measure must also be considered.

Furthermore, the extent of the efficiency increase must be placed in relation to the consumption and costs per unit and placed in the larger context (e.g. of the company) in order to be able to better classify the “weight” of the efficiency increase and the associated subsequent effects. Table 2 shows an approximation of these characteristics through various questions.

The following questions can provide guidance in this regard:

- Does the efficiency measure achieve its set goal (i.e., is the planned/expected increase in efficiency realized)? Or are there already efficiency deficits in or directly after the implementation of the measure, which could in principle be closed by improving the implementation?
- What is the size of the actual savings of physical resources? How and to what extent are costs also reduced as a result? What is the proportion of physical and financial savings compared to total (unit) costs?

- How does the size of the efficiency improvement relate to the total costs and consumption of the company? Does this represent a substantial increase in efficiency? Or is the financial impact rather small?
- Does the increase in efficiency offer other, different benefits to the company?
- Does the increase in efficiency change the stakeholders' assessment of the environmental impact of the procedure, process or product?

The direct consequences and associated benefits of efficiency measures listed here form a necessary but not yet sufficient condition for the emergence of rebound effects. A change in behavior, i.e. a decision and/or subsequent activity, must be added to these original causes in order to lead to rebound effects. These decisions and activities are the subject of the following chapter and thus also show the scope for decision-making and action for the players in companies in order to be able to counteract the emergence of rebound effects.

3.3. Typology of company-related rebound effects

Building on the process model outlined in Chapter 3.2, the financial and technological benefits of efficiency improvements are linked in the following to changes in decisions and activities in companies that can explain the emergence of rebound effects. The typology of firm-related rebound effects presented below builds on the existing literature (in particular the typology of Santarius 2016). However, it gives more space to the formation process of rebound effects by focusing more on the role of decisions to exploit the benefits of efficiency improvements and the subsequent activities in companies.

The starting point for all types of rebound effects described below is a successfully implemented efficiency measure with financial, ecological or technological benefits. The decisions made by companies following the efficiency improvement can be seen as the key factors in the development of rebound effects. Additionally, the decisions to exploit the benefits of higher efficiency are likely to be made before the implementation of the efficiency increase or to be a decisive reason for its implementation. For a better understanding of company-related rebound effects, it is therefore important to embed the efficiency improvements in the company's target system, because only these other targets allow a (causal) explanation for the reduction or absence of ecological protection due to rebound effects.

The key questions this section explores are therefore: Why are efficiency improvements made and what are the associated financial, environmental and technological benefits used for? What decisions and activities are associated with them? How and why do company-related rebound effects arise?

In the following, we describe different types of firm-related rebound effects that explain higher-than-expected resource consumption based on efficiency gains. These effects, which reduce the environmental benefits, thus arise from a specific use of the financial and technological benefits to pursue different goals of the companies. Central to this are decisions about production and sales of existing products and services, the design of core and support processes in production and the provision of services, product development and design, and the scope of the product portfolio. Depending on the characteristics of these decisions and the subsequent activities to implement them, higher than previously expected resource consumption can be assigned to the following types of rebound effects:

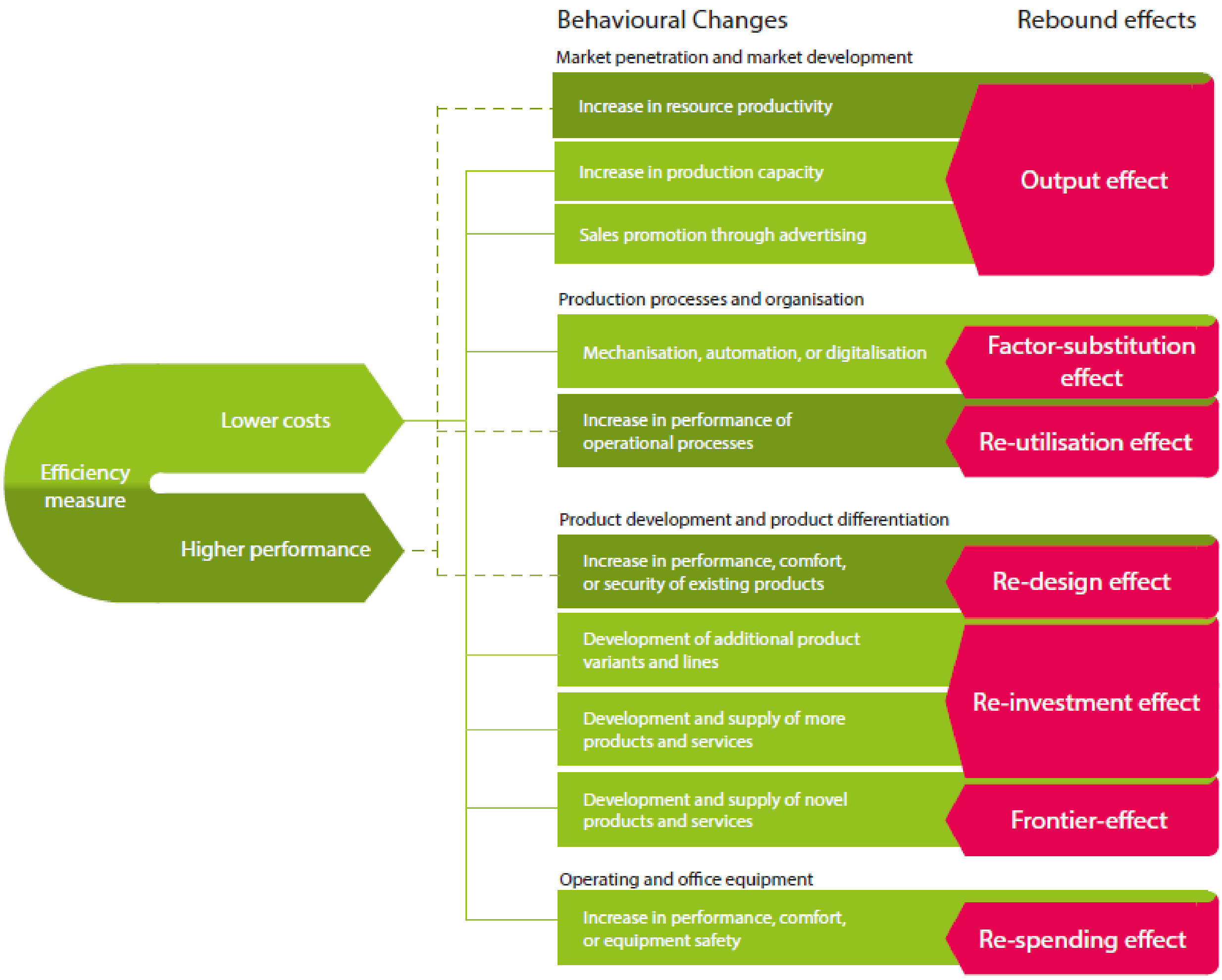
- **Output effects** that result from an increase in production and sales for market penetration and development;
- **Factor substitution effects**, which result from the exchange of production processes and the associated increase in the use of energy services;
- **Re-utilization effects**, which result from performance-enhancing changes in production processes and production organization;
- **Re-design effects**, which result from performance-enhancing changes in product design;
- **Re-spending effects**, which arise from using saved additional financial resources for regular current expenditures;
- **Re-investment effects**, which arise from using accumulated financial savings for product development, product differentiation or diversification;
- **“Frontier” effects**, which arise from the development of entirely new products and services.

Figure 3 provides a graphical overview of the pathways leading to these different rebound effects. Starting from the increase in efficiency, the next sections explain the decisions to use the financial and technological advantages and the subsequent activities of companies as explanatory approaches for company-related rebound effects. These behavioral changes then allow the higher-than-expected resource consumption to be linked to an action perspective. A tabular overview of the types with practical examples can be found in the appendix to this paper.

The widely used distinction between direct and indirect effects is a problematic foundation for categorization which, in a simplifying and abstracting manner, only functions heuristically at the level of what happens in companies (for example, a re-investment of cumulative financial resources saved due to the increase in efficiency in the expansion of production capacity; this re-investment in the increase in existing output can thus be seen as a hybrid form of a direct and indirect effect). The explicit classification as a direct or indirect effect is therefore not pursued here. Rather, we assume that a continuum from direct to indirect rebound effects exists.

Since efficiency increases can also have spatially and temporally distant consequences, especially due to indirect effects, more than four steps are therefore conceivable. The choice of the system boundaries and the period under consideration is thus of central importance for the size of the rebound effect (Greening et al. 2000; Font Vivanco & Van der Voet 2014). In the following, the process from the increase in efficiency via the subsequent decisions and activities to the resulting rebound effects is described.

Figure 4: Emergence of different types of rebound effects



Source: Wolff et al. (2023).

3.3.1. Output effects through expansion of sales

In the case of output effects, higher-than-expected resource consumption results from the use of the financial and technological advantages of higher efficiency when these are used to expand production and sales volumes. This can occur with or without cost savings within the company, and in the case of cost savings with or without price reductions by the company.

Sales expansion due to higher resource productivity (by exploiting material efficiency gains)

Increasing efficiency makes it possible to provide more products or services from the same amount of resources. If production is expanded accordingly, the savings associated with the increase in efficiency are lower than would theoretically be possible. Even without reducing costs and lowering prices, production and sales can be expanded in this way.

Sales expansion due to cost savings (by using financial efficiency gains to increase output)

With price reduction: The increase in efficiency leads to lower costs in core and support processes of the company in the provision of products and services. If these financial efficiency gains are passed on in full to consumers in the form of lower prices, this leads (c. p.) to higher demand and, in the case of available (production) capacities, to an expansion of the production volume.

Without or with only a partial price reduction: The increase in efficiency leads to lower costs, which are, not or only partially passed on to consumers as price reductions. The remaining financial efficiency gains are used for sales promotion (advertising, etc.) or (after cumulation) invested in increasing the production capacity of the same output.

In summary, theoretically possible savings are in all cases converted into higher output of existing products and used for market penetration (of the same sales market) or market development (of new sales markets).

3.3.2. Factor substitution effects through changes in production processes

Factor substitution effects occur through the use of financial and technological advantages to improve performance in core and support processes and operational functions. Increasing mechanization, automation and digitalization allow substantial efficiency gains compared to human labor. The efficiency gains of production equipment, processes and technologies, when considered in isolation, can lead to resource savings in their operation or use. The use of such energy services, i.e. the use of energy by plant and machinery, thus becomes more favorable compared to human labor for the same production volume. As a result, the increase in efficiency changes the relative costs between different production factors at the same level of output. This creates incentives for companies to rely more on (energy-based and comparatively more resource-intensive) mechanization, automation and digitization instead of using human labor. If substitution increases over time, there will be a shift in the factor mix toward energy services. This increases energy and resource intensity; potential savings from the original increase in efficiency are reduced or eroded by the increasing use of these energy services. As a result, the reductions in resource consumption are lower than theoretically possible.

Theoretically possible savings in energy services (before substitution) are reduced or eroded due to the increased use of these energy services. In the process, the increased use of energy replaces human labor in particular.

3.3.3. Re-utilization effects through process improvements

In the new re-utilization effect introduced here, the technological and financial benefits of efficiency improvement are used to improve the performance of core and support processes and operational functions. The efficiency improvement enables lower resource consumption in the use of technologies, processes and operational functions. However, these theoretical savings opportunities are not brought about, or are brought about only partially, as the efficiency improvement is used to increase the performance of technologies, processes and operational functions. Analogous to the re-design effect (see below), savings in resource consumption on the input side are consumed by increases in performance on the output side of the process. In the course of increasing efficiency, the company uses additional energy/materials to better achieve existing purposes (e.g., process and product quality) in core and support processes 1) more intensively, 2) more extensively, and/or 3) more frequently.

Theoretically possible efficiency improvement savings are thereby converted into process/product quality or employee satisfaction.

3.3.4. Re-design effects through performance enhancement of products and services

Re-design effects occur when the use of technological and financial benefits of efficiency improvement is used to improve the performance of products and services. The advantages of efficiency enhancement enable (potentially) lower resource consumption for products and services in the use phase. However, these are not fully used to reduce resource consumption, but the savings potential of efficiency improvements are also used to increase performance or otherwise improve benefits (comfort, safety, etc.) in terms of (presumed) consumer preferences.

Theoretically possible savings are thereby converted into performance improvements and thus into (presumed) customer benefits.

3.3.5. Re-spending effects from additional resource consumption due to short- to medium-term spending

The increase in efficiency leads to lower costs, which are, not or only partially passed on to consumers as price reductions. The resulting financial savings are used for short- to medium-term expenditures, which in turn (can) trigger resource consumption. From an overall company perspective (or an even more comprehensive perspective, e.g. in the case of payments to employees or shareholders), the reductions in resource consumption are lower than theoretically possible.

Theoretically possible savings are partially consumed or (over)compensated by other resource consumption triggered by expenditures.

3.3.6. Re-investment effects from additional resource consumption due to cumulative re-invested financial efficiency gains

The increase in efficiency leads to lower costs, which are, however, not or only partially passed on to consumers as price reductions. The financial savings add to financial budgets over time. These can then finance medium- to long-term investments, which in turn (can) trigger resource consumption. These include the development of further products and services as well as diversification. As a result, the production and thus the output of these new products and services can be expanded.

Theoretically possible savings are partially consumed or (over)compensated by other resource consumption triggered by investments.

3.3.7. “Frontier” effects through the development of completely new products and services

Financial and technological advantages are used to develop entirely new types of products and services. This is made possible by more efficient technologies or their combination. The increase in efficiency or various increases in the efficiency of technologies in combination enable the development of completely new types of applications, products and services. This technical progress leads to the emergence of new product categories and industries, the production of which in turn triggers new resource consumption.

Theoretically possible savings through efficiency improvements are reduced or eroded by the manufacture and use of additional products and additional production and application possibilities. The transformation or production curve is shifted outward.

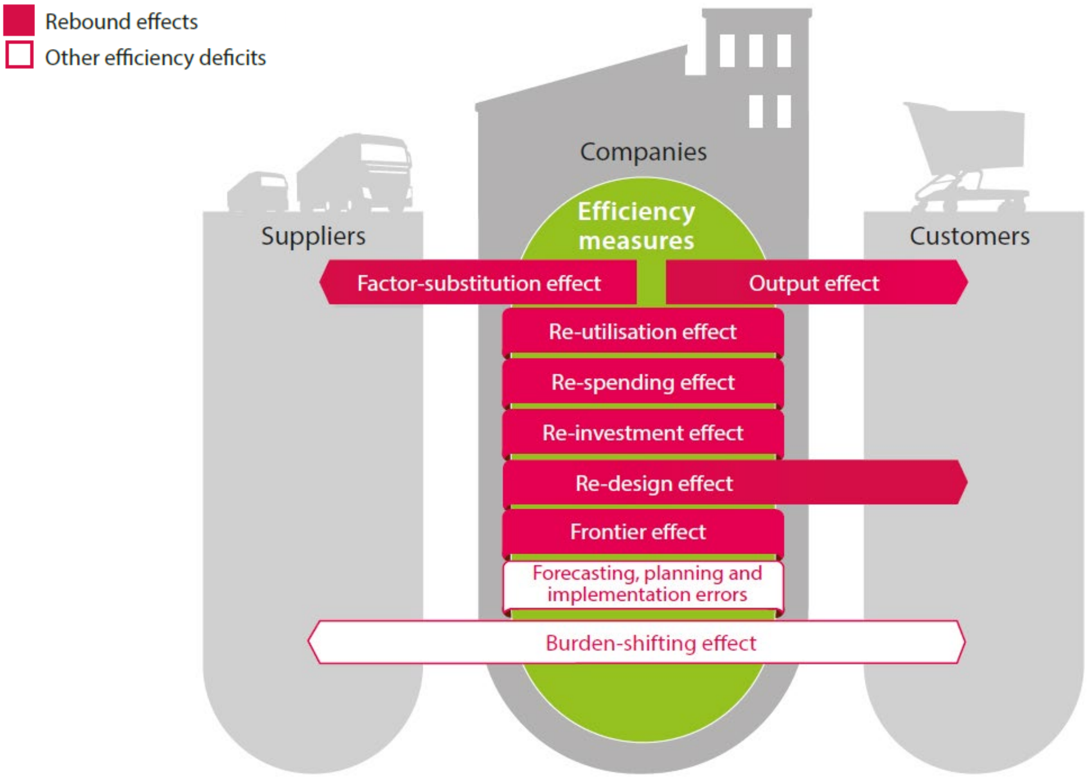
3.4. Rebound map: location of rebound effects in the value chain

In the following, the individual rebound effects from the rebound typology of chapter 3.3 and the other impact deficits of efficiency measures mentioned in chapter 3.1 are located on a "**map**" that schematizes the value chain. In this way, we aim to show which **actors** within the value chain contribute to the development of rebound effects and other impact deficits of efficiency measures through behavioral changes. More explicitly than in previous research, the link between companies and other actors in the value chain will be established in order to show the "**locations" of the emergence** of rebound effects in the interaction of production and consumption as well as their interactions. **Customers** and **suppliers** are thus conceptually included in the consideration of rebound effects. The map of possible rebound effects thus reflects the observation that often at least two actors or groups of actors are involved in the creation of rebound effects (cf. Figge et al. 2014).

Figure 4 shows that factor substitution effects can arise in the **supply chain** and in the **procurement markets** on one side, and burden shifting effects on the other, i.e. upstream energy and material consumption caused by efficiency improvements in the **company**. Forecasting, planning and implementation errors can be located in the company itself, but also re-utilization, re-spending and re-investment effects. **Sales markets** and **customers** are involved when output, re-design and frontier effects arise. Rebound effects differ depending on whether they occur in the context of existing products (re-design), additional products (re-investment effects as a result of product differentiation and diversification) or completely new products (frontier effects).

In the graph, the genuine rebound effects (or the processes that can lead to them) are shown in red; the similar effect deficits (burden shifting; forecasting, planning or implementation errors) are drawn in white with a red box around them.

Figure 5: Mapping rebound effects in the value chain



Source: Wolff et al. (2023).

The rebound map also maps the conceptual (**system) boundaries** for company-related rebound effects. Possible demand effects due to price changes on commodity markets (cf. Santarius 2015), for example, are thus not taken into account, even if these can arise from the activities of a large number of companies (i.e. the effect of an industry-wide implementation of technologies for higher resource efficiency).

The rebound map highlights the phenomenon of previously-marginalized **indirect** company-related rebound effects and thus strengthen the understanding of such indirect effects – especially re-design and re-investment effects. These effects are partly controversial as rebound effects, since resource consumption occurs outside of the time and space of the original efficiency increase.

It is also important to note that the effects shown in the map do **not** (or cannot) all have a **simultaneous** effect, as financial savings from efficiency improvements cannot be used more than once. However, it is also conceivable that the various effects will take effect simultaneously, but only on a **partial basis**. The purpose of the presentation is to provide an overview of rebound effects that is as complete as possible. The collection of possible paths to company-related rebound effects should allow us to understand why the resource savings observed in retrospect will have turned out to be lower than previously assumed.

3.5. Possible causes of rebound effects

Within the rebound typology, we have clarified the "sources" or triggers of rebound effects – from factor substitution processes to changes in production processes and organization (re-utilization) to re-investment and re-design. However, these sources are not causes or drivers that help us to understand why corresponding processes lead to rebound effects.

In the following, we want to supplement the process perspective developed above with a **causal perspective** on the emergence of rebound effects. Against the background of different bodies of literature, we develop **propositions** on which factors promote the emergence of rebound effects or have an impact on the fact that companies try to identify and manage rebound effects. In doing so, we take up explanatory approaches that are already used in the rebound literature (cf. chapter 2.2). However, we also bring into play propositions that can be derived from other bodies of literature which, to our knowledge, have not yet been made usable in connection with rebound effects.

In the **MERU project,** the propositions serve to structure and focus the evaluation of the (qualitative) empirical (case study) results and thus enable the identification of regularities and patterns. A strict “testing” of operationalized hypotheses cannot take place due to the small number of cases (ten companies, 22 investigated efficiency measures). In fact, the hypotheses are intended to allow hypothetical conclusions to be drawn from the individual and a rule to a regularity in an “abductive” sense (Friedrichs & Kratochwil 2009).

Proposition 1 (corporate strategic prioritization): The identified rebound effects are primarily due to the fact that the company prioritizes other operational purposes over the avoidance of rebound effects. Instead of maximizing the ecological benefit of the measure, losses in its ecological effectiveness are accepted, particularly in order to exploit its financial or technological benefits (see Chapter 3.2.2). Indirectly, the company is trying to improve its competitive position – through higher profits, stabilization of market share, growth, or even through improved product quality or greater employee satisfaction. Behind the corporate strategic prioritization, deeper causes can be identified. These include a lack of recognition of the ecological relevance of rebound effects in the company or ecological problem pressure in the broader sense. An orientation towards normality and 'common' practices (such as the “growth paradigm”) in the corporate environment (“mimetic pressure”) also promotes a corresponding setting of priorities in the company. Finally, economic-technical conditions/developments (low productivity growth, high cost or competitive pressure, etc.) can also lead companies to use the (material/financial) efficiency gains in a competitive-strategic way.

This proposition is supported on the one hand by approaches of sustainability-oriented strategic management (Schaltegger & Wagner 2019; Gazzola & Colombo 2014; Lamberti & Lettieri 2009; Figge et al. 2002), and on the other hand by sociological institutionalism (Powell & DiMaggio 2012, Hoffman 2001; Hoffman & Jennings 2018, Lounsbury et al. 2018).

Proposition 2 (knowledge, instruments and organizational structures): The identified rebound effects occur primarily due to the lack of relevant knowledge, instruments and organizational structures in the company to capture and manage rebound effects:

- **Knowledge** e.g. on resource consumption of industrial equipment, cost of consumption, size of financial efficiency gains, use of financial efficiency gains.
- **Instruments** for creating the relevant knowledge, e.g. key figures within environmental or energy management systems; financial controlling that considers the use of freed-up funds; procurement criteria

- **Structures**, e.g. routines, degrees of freedom, communication channels, which enable a system understanding of mutually influencing resource consumption and allow coordination between different areas and operational functions affected by the measure – and thus “process control”.

This proposition is supported by instrument-related strands of the sustainability-oriented strategic management literature (e.g., Baumgartner 2014; BMU et al. 2007; Figge et al. 2002; Johnson & Schaltegger 2015).

Proposition 3 (psychological factors): The identified rebound effects are primarily due to the fact that actors in the company (e.g. decision-makers, developers, users) perceive the technology/process or their entire actions as less harmful to the environment after successful implementation of the efficiency measure and consequently change their behavior and intensify resource consumption. Different psychological phenomena play a role here, such as 1. the perception of self-efficacy and the diffusion of responsibility or 2. moral licensing. In the first case, the reduction of consumption/emissions of a technology by an efficiency measure leads to the fact that the persons involved attach less importance to their individual use behavior, because they attribute a lower effect to it and see a lower individual responsibility for an environmentally friendly use. As a result, the technology in question is used more intensively in the application phase. In the second case, the motivation of the individuals involved to become more eco-efficient in other (sub-)areas decreases after the efficiency measure, and the increase in efficiency is subsequently used to morally justify environmentally damaging behavior in other (sub-)areas of the company.

This proposition is supported by individual psychological explanatory models such as the theory of planned behavior (Ajzen 1991) and Schwartz's (1977) norm-activation model, which in turn have been applied in consumer-based rebound research by Peters et al. (2012) and Santarius & Soland (2018).

What is the **relationship** between the **causes** of rebound effects mentioned in the propositions **and** the **types of rebound effects** identified above? We do not assume that certain types of rebound can only be caused by certain drivers. Rather, each type and also each individual case of rebound effect can be caused by any one or even several of the drivers described in the propositions. Different drivers can thus also **interact**. For example, the emergence of a rebound effect can be enabled by a company's failure to collect data to monitor the development of consumption after the implementation of efficiency measures (Proposition 2). This omission can in turn be indirectly attributed to the fact that management prioritizes other operational goals (Proposition 1). This suggests that the propositions are **not** entirely **independent of each other**.

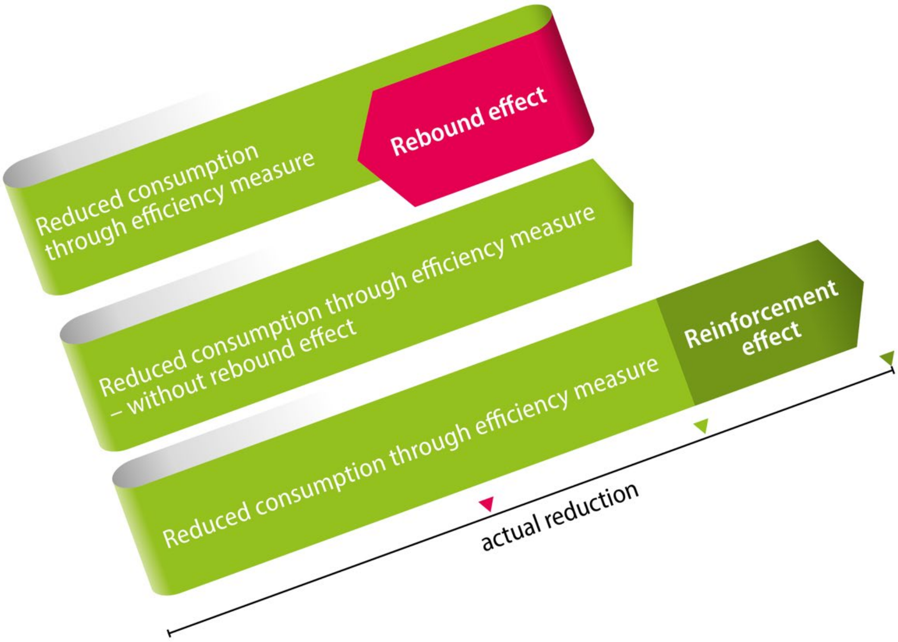
4. Conclusion

Rebound effects in companies are a complex phenomenon that has seen little empirical research. In this paper, we first approached the phenomenon by reviewing the state of the art in research and then developed our own **(“MERU”) concept of firm-related rebound effects**. We understand company-related rebound effects as a **specific impact deficit** of corporate efficiency efforts, where the theoretically possible and expected reductions of energy and material consumption are not or not fully achieved by an efficiency measure. In this understanding, efficiency measures or gains are the starting point and trigger of rebound effects. Other possible implementation and impact deficits of efficiency measures partly occur before and during an efficiency increase (in the case of burden shifting, forecasting, planning and implementation errors) and not only afterwards, as is characteristic for the rebound effect. We have created a process model and developed propositions on the causes or drivers of the emergence of company-related rebound effects. From the literature, but also from empirical insights into the emergence of rebound effects gained in the MERU project, we have developed a typology of seven company-related types of rebound effects: Output, Factor Substitution, Re-Utilization, Re-Design, Re-Spending, Re-Investment, and Frontier effects. Some of the types are known from previous rebound research, others (especially the reutilization effect) have not yet been described in the literature but could be identified empirically in MERU's empirical case studies. The individual types of rebound effects can be located at different points along the value chain.

The discussion of rebound effects also shows that they are a **relative phenomenon** at the company level. Whether rebound effects can be diagnosed depends on the degree to which subsequent additional consumption is already considered when calculating savings potential: If such additional consumption is not expected and accordingly not priced into the “theoretically possible savings”, rebound effects arise in the calculation. However, if they are expected and considered, the rebound effect phenomenon does not occur at all. The reduction in the efficiency effect is considered in advance in exactly the same way as the environmental effects from the manufacturing of a device (e.g. a thermostat) that serves to increase efficiency. Thus, rebound effects are a *non-expected consequence* of efficiency measures only if there was an expectation that resource consumption would decrease more in absolute terms in the end. Finally, rebound effects are a *non-expected or unanticipated consequence* only if companies are unaware of the mechanisms by which rebound effects arise.

Rebound effects in companies should not be interpreted to mean that **corporate efficiency efforts** are useless. As a rule, efficiency measures (except in the case of a “backfire” effect) lead to resource savings despite deficits in effectiveness, and these are indispensable in order to be able to set planetary boundaries and maintain room for maneuver. What is needed, however, is a greater awareness in companies that efficiency measures often do not produce the theoretically possible savings, and that different decisions and activities after implementation of the efficiency measures have a decisive influence on their ecological effectiveness. The process model indicates where companies can start – for example, by monitoring resource savings effects and controlling financial flows – in order to implement efficiency measures as ecologically effectively as possible. Comprehensive management of energy and resource efficiency takes into account not only rebound effects but also other efficiency deficits – e.g. those outside the company – and strategies beyond efficiency (e.g. consistency, sufficiency). An ambitious strategy for dealing with impact deficits of efficiency measures makes it possible not only to reduce the difference between the theoretically expected savings from an efficiency measure and the savings actually achieved, but to use it in such a way that the efficiency measure is positively reinforced. We then speak of a **reinforcement effect** (Schaltegger, Amend & Wüst, in print), cf. Figure 5.

Figure 6: Schematic presentation of the reinforcement effect



Source: own.

The figure shows schematically that an energy or material efficiency measure can either lead to a rebound effect (upper strip); that it can be implemented without causing a rebound effect (middle strip); or that it can be accompanied by a reinforcement effect (lower strip). This requires an active rebound management (Wolff et al. 2023).

The causes of rebound effects identified above (Chapter 3.5) can also be used as **levers for** such **amplification effects**: a corporate strategic prioritization of the ecological effectiveness of efficiency measures (e.g. by embedding efficiency measures in 'strong' sustainability strategies or corporate self-restraint/post-growth approaches); the development of knowledge, tools and organizational structures for recording and managing rebound effects. by embedding efficiency measures in 'strong' sustainability strategies or entrepreneurial self-restraint/post-growth approaches); the development of knowledge, tools and organizational structures to capture and manage rebound effects; as well as the awareness of psychological rebound mechanisms among employees in all functions of the company – from purchasing to product design and production to marketing – can help to positively amplify the impact of efficiency measures (Gebauer 2022; Schaltegger, Amend & Wüst, in print).

Finally**, in the political arena**, efficiency deficits and rebound effects should be considered in the context of public efficiency strategies: Theoretically achievable efficiency gains do not fully translate into decreasing resource consumption when companies and consumers want to use or fulfill new needs, wants, growth opportunities, etc.

5. Literature

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