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Energy efficiency and rebound effects in German industry – evidence from macroeconometric modeling

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ABSTRACT

Increases in energy efficiency are reduced by the rebound effect. Efficiency gains on the micro level do not lead to proportionate reductions of energy consumption on the macro level. The German energy-economy model PANTA RHEI is applied to better understand the rebound effect. To get more robust estimates micro data from a cost structure survey of the German manufacturing sector was used to derive price elasticities of energy demand. The mesoeconomic rebound effect of an autonomous increase in energy efficiency at the industry level in manufacturing is between 7% in 2021 and 12% in 2030. The macroeconomic rebound effect lies between 12% in 2021 and 18% in 2030. Inclusion of necessary investment and assumptions of higher elasticities of substitution increase the effects. Rebound effects limit the scope of technology-driven efficiency improvements and must be considered in the design of ambitious energy efficiency programs and climate policies.

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Rebound effect; input–output model; energy efficiency; macroeconomic effects; climate policy

1. Introduction

In the literature, there is a broad consensus that rebound effects exist and are a major reason why energy efficiency increases do not translate into a reduction in energy consumption to the same extent. Survey articles such as Chakravarty et al. (2013) and Brockway et al. (2021) show a range of these effects from near zero (no rebound) to greater than one (backfire). However, it is not only the estimates of the size of the rebound that vary considerably, but also macroeconomic models and modeling approaches used differ in many cases. The methods can certainly not (only) explain this range. In a comparison of eight CGE models for different countries, Allan, Hanley, et al. (2007) show that the economy-wide rebounds range considerably from 37% to over 100%. A comprehensive literature review can be found in Lange et al. (2019), in which various forms of rebound effects and methods for capturing them are discussed. Impacts can be divided into micro-, meso- and macroeconomic and global rebound effects, whereby all underlying effects must be included when considering the respective levels (Lange et al., 2021). Microeconomic effects take place on the individual level of an economic unit, i.e. a consumer or company, where a distinction can be made between direct and indirect as well as substitution and income effects. Mesoeconomic effects are those that affect the next higher level of aggregation, i.e. groups

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of individual actors as markets and sectors. Macroeconomic effects have an impact at the national and global effects at the international level. In addition to effects on international trade, energy prices and macroeconomic multipliers are considered.

As depicted by Lange et al. (2019), three fundamentally different methods are suitable for the analysis of rebound effects: theoretical approaches, empirical ex-post studies and model-based ex-ante analyses. Macro rebounds are generally determined using three types of economy-wide models in ex-ante analyses. These are macroeconomic (growth) models that are closely linked to economic theory (e.g. Saunders, 2000), computable general equilibrium (CGE) models that assume optimization behavior of companies and households at the microeconomic level according to neo-classical theory emphasizing the supply side, and macroeconometric models that set the behavioral parameters based on empirical observations and include the demand side to a greater extend. The latter two model types contain the industrial structure of the economy based on input–output tables.

In a similar manner, Colmenares et al. (2020) differentiate between neo-classical growth models, econometric models and simulation models with integrated assessment models being distinguished as a fourth model type. A study for the European Commission (Pollitt et al., 2017) distinguishes between (i) (static) input–output models used for multiplier analyses, (ii) supply-oriented CGE models and (iii) demand-oriented macroeconometric models. A similar distinction can already be found in IEA (2014). West (1995) compares CGE, IO and IO plus Econometric models on the regional level.

Findings for economies that are difficult to compare to Germany may not be transferable, which further limits the choice for comparing relevant approaches. This applies to studies looking at a rapidly growing emerging market economy such as China (Lin & Li, 2014; Zhou et al., 2018) as well as to an economy with high energy production such as the US, which is oriented towards the domestic market (Böhringer & Rivers, 2018; Rausch & Schwerin, 2018).

Various model-based analyses of rebound effects were selected in Banning and Lutz (2019) based on the following criteria: the model considered (i) examines a macroeconomic or economic-wide rebound as defined in Lange et al. (2019), (ii) is explained in sufficient detail, which allows for the examination of influencing factors, underlying assumptions, and variables, and (iii) is presumably of relevance for the modeling approach in section 3 not only because of this detailed information but also because of the regional coverage and the capturing and mapping of rebound effects. Three of these are examined in more detail below.

Both Allan, Hanley, et al. (2007) for the UK and Koesler et al. (2016) with focus on Germany in the international context apply CGE models. Following the optimization decisions of agents, markets generally clear and reach equilibrium via price changes in CGE models (EC, 2017). However, especially in the context of energy efficiency, the barriers to the implementation of new technologies could be underestimated in this type of models with high elasticities of substitution (Sorrell et al., 2004).

The model MDM-E3 (Barker & Foxon, 2008) combines econometric time series analysis and input–output data. The modeling of demand and investment is (post-) Keynesian, whereas the supply side is also represented by equation systems. Macroeconometric models generally offer comprehensive explanations of the adjustments of an overall economy to changing conditions (Allan, Gilmartin, et al., 2007). Table 1 gives an overview of major

Table 1. Overview over central model characteristics.

	Allan, Hanley, et al. (2007)	Barker and Foxon (2008)	Koesler et al. (2016)
Model type	E3-CGE (UKENVI)	National macroeconometric model (MDM-E3)	Multi region CGE world model
Production function	Multi-level production functions (CES, sector-specific)	No explicit production function: factor demand estimated individually	KLEM (CES, sector/country specific)
Number of sectors	25(5 of which energy)	50 industries,4 sectors: 50 fuel users	8 (2 of which energy) per country
Elasticity of substitution	0.3 (between energy and non-energy components)		Between 0.15 and 0.72 depending on sector
Rebound effects	Electricity production:62% short term, 27% long termRemaining energy production:55% short term, 31% long term	Macro rebound (by their definition): 11%Direct rebound: 15% (exogenous to the model)Total rebound: 26%	47–57%, depending on scope and scenario
Causal shock	Rise in energy productivity by 5%	Various policy measures	Rise in energy productivity by 10%,
Effect on GDP	+0.11% to +0.17%	+1.26%	Germany: +0.13% to +0.5%

Source: Banning and Lutz (2019).

characteristics of the three models that are most relevant for comparison with the modeling approach in Section 3.

Elasticities of substitution of energy and other input factors are important for the model results and the level of rebound. Allan, Hanley, et al. (2007) assume a value of 0.3 for the elasticity of substitution between energy and non-energy components, as well as for the elasticity of substitution between intermediate consumption (including energy) and value added. Koesler et al. (2016) use a substitution elasticity for each of the eight sectors of their model at each of the three levels of their production function. The value of the elasticity of the energy component to labor and capital ranges between 0.15 (construction) and 0.72 (coke, refined petroleum, and nuclear fuel), in the manufacturing sector the median value is 0.53. Barker and Foxon (2008) estimate different factor demand functions, i.e. there is no explicit production function in the model and price elasticities of energy demand are sector-specific.

The MDM-E3 model shows a macro rebound of 11%. To calculate the total rebound, the exogenous direct rebound effects of 15% are added to the model output, so that the total rebound amounts to 26%. The long-term economy-wide rebound in the UKENVI model is comparable at 27% and 31%, depending on scenario assumptions. The short-term rebound effects for the electricity and other energy sector are significantly higher 62% (55%) in the long term. In Koesler et al. (2016), rebound effects are generally higher (47–57%). Starting point for the rebound effect is an increase in energy efficiency in all models, with the cause, extent and sectors affected differing. The changes in energy consumption in contrast to the original value are then compared with the increase in energy efficiency to calculate the rebound. In the MDM-E3 model, the increase in efficiency is mapped by various policy measures or programs that have been adopted.

Increased energy efficiency improves the productivity of the economy and leads to an increase in GDP, which can be an important driver of rebounds. Allan, Hanley, et al. (2007) come to the conclusion that the 5% increase in energy productivity leads to a 0.11% increase in GDP in the short term, while the difference increases to 0.17% in the long term. Koesler et al. (2016) report a small positive effect on German GDP (+0.13% and +0.51%, respectively). Barker and Foxon (2008) show a GDP increase of 1.26% in the UK compared to the reference scenario induced by the energy efficiency measures. The increases in GDP are much lower than the rebound effects, which means that the induced increase in economic activity cannot explain most of the rebound effect, if it leads to a proportional increase in energy consumption.

This literature review shows that the elasticities of substitution that are decisive for the rebound effect are mostly assumed or taken from the literature often adopted from other countries. Efficiency gains as the starting point of rebounds are exogenously set. Only in the case of Barker and Foxon (2008) concrete policy measures in the UK drive them.

In the approach below, the applied price and output elasticities of energy demand by industry are derived from econometric estimation. Explicit energy efficiency improvements and related investment from recent impact assessment for the German NECP are used. This is where the following analysis breaks new ground.

The aim of this review has been to gain insights for simulations of macroeconomic rebound effects using the macroeconometric model PANTA RHEI, which is described in section 2. Section 3 presents results for modeling rebound effects for Germany, assuming an increase in energy efficiency in manufacturing from 2021 to 2030, including two sensitivity analyses. Some conclusions and an outlook on follow-up research to design and model policies to cap or reduce the rebound effects close the paper in section 4.

2. Materials and methods

2.1. Overview

The national economy-energy-environment model PANTA RHEI, which is applied in section 3, is an environmentally extended version of the econometric simulation and forecasting model INFORGE for Germany (Ahlert et al., 2009; Zika et al., 2018). It is an INFORUM-type dynamic model with a time series of input–output tables at its heart. A detailed description of the economic part of the model with a focus on the labor market is presented in Maier et al. (2015). The most important equations regarding rebound effects are presented below. For details of the complete model see Lutz (2011) and Lutz et al. (2005). Among others, it has been used for economic evaluation of different energy scenarios that have been the basis for the German energy concept in 2010 (Lindenberger et al., 2010). Applications include an evaluation of employment impacts of renewable energy promotion (Lehr et al., 2012), socio-economic impacts of the German energy transition (Lehr et al., 2019; Lutz & Lehr, 2020; Lutz et al., 2018, 2021), impacts of the transition to a green economy (Lutz et al., 2017) and economic effects of an e-mobility scenario (Ulrich & Lehr, 2020).

The behavioral equations reflect bounded rationality rather than optimizing behavior of agents. All parameters are estimated econometrically from time series data (1991–2017). Producer prices are the result of mark-up calculations of firms. If costs are reduced due to higher energy efficiency, producer prices will c.p. also be lower. Output decisions follow observable historic developments, including observed inefficiencies rather than optimal choices. The use of econometrically estimated equations means that agents have only myopic expectations. They follow routines developed in the past. This implies in contrast to optimization models that markets will not necessarily be in an optimum and non-market (energy) policy interventions can have positive economic impacts.

The parameters of other structural equations are also econometrically estimated. In the model-specification stage, various sets of competing theoretical hypotheses were empirically tested. As the resulting structure is characterized by highly nonlinear and interdependent dynamics, the economic core of the model has furthermore been tested in dynamic ex-post simulations. The model is solved by an iterative procedure year by year and modeling is usually bottom-up. This means that calculations are made at sector level and macro variables are calculated as a sum.

2.2. Economic model

A fundamental difference to CGE models, which use a nested production function, is the determination of output. Multiplying the Leontief-inverse $(I-A)^{-1}$ – A is the input coefficient matrix and I is the identity matrix – with the final demand vector fd_i gives gross production Y_i for each of the 63 industries i of the German input–output table considered.

$$Y_i = (I-A)^{-1} * fd_i \tag{1}$$

Components of final demand such as private consumption, government consumption and different kinds of investment are modeled at the industry level (see Maier et al., 2015). They depend on activity variables such as disposable income, production or capital coefficients and relative prices.

Final demand is the sum of private consumption c_i, government consumption g_i, investment inv_i for equipment, construction and software, and exports ex_i minus imports im_i.

$$fd_i = \mathrm{c}_i + g_i + inv_i + ex_i - im_i. \tag{2}$$

Private consumption patterns by 41 purposes of use c_k are estimated as a function of real disposable income $\frac{YH}{PC}$ and relative prices $\frac{pc_k}{PC}$. PC denotes the consumer prices index. For some consumption purposes, time trend t as proxy for long-term change in consumption behavior or the number of private households HH is used as explanatory variable.

$$c_k = f\left(\frac{YH}{PC}, \frac{pc_k}{PC}, t\right) \tag{3}$$

Via a constant bridge matrix from the Federal Statistical Office consumption is transferred into demand for 63 consumption goods groups c_i.

Government expenditures depend on the disposable income of the government (YG), employment (Emp) as well as demographic change (Pop).

$$g_i = f(YG, Emp, Pop) \tag{4}$$

Gross fixed capital formation is separately modeled for investment in equipment, construction, and other facilities on sector level as a function of production y_i, in a few cases also of the capital stock k_i and a trend t.

$$inv_i = f(y_i, k_i, t) \tag{5}$$

The investments increase the capital stock k_i. Consumption of fixed capital then results from fixed quotas in the capital stock.

Export demand in current prices is set exogenously to meet baseline assumptions of GDP growth until 2030 from Prognos, Fraunhofer ISI, et al. (2021). Exporters just react to domestic price changes. The influence of this assumption on rebound effects is tested in a sensitivity analysis.

Import demand is estimated separately at the sectoral level for intermediate iid_i and final demand ifd_i as a function of production y_i and the price relation of import price pim_i and domestic price p_i.

$$iid_i = f\left(y_i, \frac{pim_i}{p_i}\right) \tag{6}$$

$$ifd_i = f\left(y_i, \frac{pim_i}{p_i}\right) \tag{7}$$

$$im_i = iid_i + ifd_i \tag{8}$$

Basic prices p_i are depending on unit costs uc_i and mark-ups. The extent to which mark-up pricing is possible depends on the market form in specific industrial sectors. Industries on international markets also have to consider import prices (pim_i) as their trade is exposed to foreign competition as well.

$$p_i = f(uc_i, pim_i) \tag{9}$$

Prices for different GDP components such as exports px_i are estimated at the sector level or by consumption use as a function of producer prices pc_i for private consumption. The consumer prices pc_i are transferred via the bridge matrix into prices for consumption purposes pc_k. The consumer price index PC is the weighted average of consumer prices pc_i.

$$px_i = f(p_i) \tag{10}$$

$$pc_i = f(p_i) \tag{11}$$

The modeling of the labor market is presented in detail in Maier et al. (2015). Labor demand functions are based on hours employees work (volume of work). This approach builds on two important observations: first, a volume-based approach to labor demand considers t growing importance of part-time employees; second, labor policy instruments such as short-time work, for example, can be explicitly addressed. Working hours h_i are determined by sector-specific production y_i. In some industries, real wages $\frac{w_i}{p_i}$ are also influential.

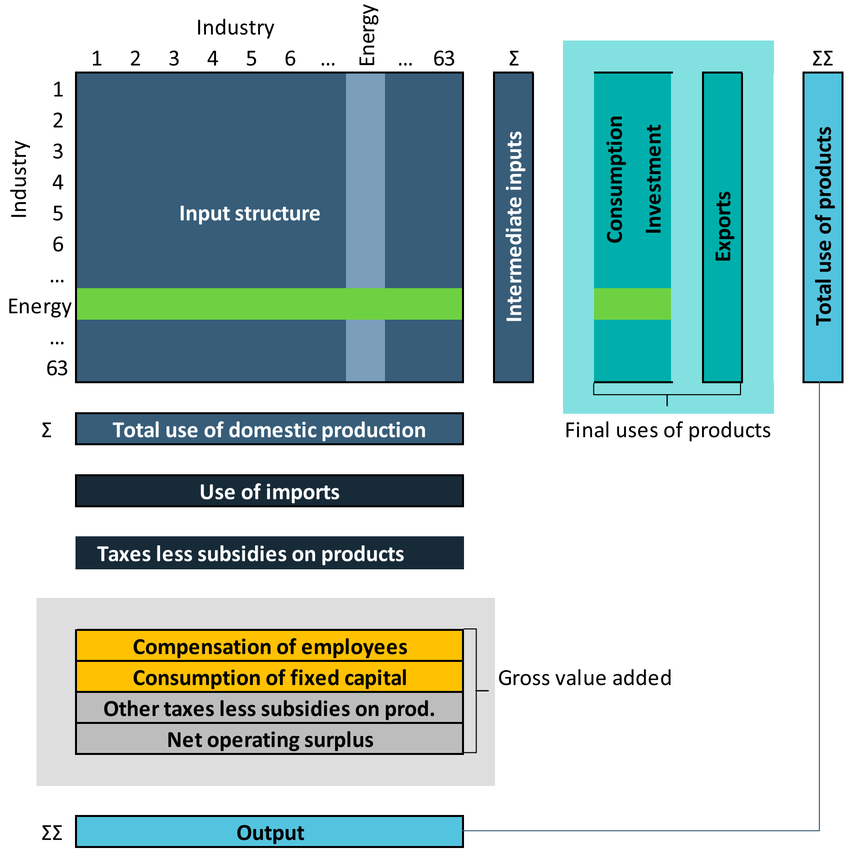
$$h_i = f\left(y_i, \frac{w_i}{p_i}\right) \tag{12}$$

Average wages W or the total economy are determined by using a Phillips curve approach. The wages depend on labor productivity $\frac{GDP}{Emp}$, the consumer price index PC and the ratio of employed people emp to the labor force LF.

$$W = f\left(\frac{GDP}{Emp} * PC, \frac{Emp}{LF}\right) \tag{13}$$

Accordingly, average wages by industry w depend on the one hand on average wages W and on the other hand on sector-specific labor productivity $\frac{y_i}{h_i}$.

Figure 1. Input–output structure of PANTA RHEI. Source: Own illustration based on Destatis (2020).



The number of employees *Emp* is derived, dividing the number of working hours h_i by working time per year and capita hy_i which is exogenous.

$$Emp_i = \frac{h_i}{hy_i} \tag{14}$$

Factor demand for labor (compensation of employees), capital (investment, consumption of fixed capital), and energy (rows of intermediate inputs and final demand, see section 2.2) is modeled in factor demand functions (highlighted in yellow and green in Figure 1). Non-energy input coefficients (intermediate inputs) are tested for price dependency, but for most inputs coefficients prices cannot explain changes over the past. Then, input coefficients – for domestic inputs and for imports – are assumed to be constant over time. In general, PANTA RHEI as a macroeconometric input–output model is less price sensitive than a CGE model, which assumes substitutability of all factor and intermediate inputs.

2.3. *Energy module*

The energy module describes the interrelations between economic developments, energy consumption and related emissions. Economic activity such as gross production of industries or final consumer demand influences respective energy demand. Energy input coefficients (energy) develop with the respective energy sources according to the energy balance. Vice versa, the expenditures for energy consumption have a direct influence on economic variables, as they represent demand and costs.

The energy module contains the full energy balance with primary energy input, transformation, and final energy consumption for 20 energy consumption sectors, 27 fossil energy carriers and the satellite balance for renewable energy. In total, the balances divide energy consumption into 30 energy carriers. Prices, also in Euros per energy unit, are modeled for different energy users such as industry, services, and private households for all energy carriers. The energy module is fully integrated into the economic part of the model.

Energy demand for 14 industries as differentiated by the energy balance $E_i$is modeled to be dependent on industry output Y_i and the relative development of energy costs, the weighted energy price index pe_i compared to the output price p_i of the respective industry. An increase in output is linked to an increase in factor demand while the relative costs of energy determine factor substitution. Ordinary least squares regression is used for estimation. Energy data by industry is taken from AG Energiebilanzen (2020).

$$E_i = \hat{\beta}_{0,i} + \hat{\beta}_{1,i} * Y_i + \frac{\hat{\beta}_{2,i} * pe_i}{p_i} \tag{15}$$

To get more robust estimates, micro data from a cost structure survey of the German manufacturing sector was used to derive price elasticities of energy demand.[1] The cost structure survey contains micro data provided and collected by the German research data centers of the Statistical Offices of the Federal States, comprising observations both at the plant and firm level from the German industrial sector. Participation is mandatory for the firms and the panel contains information on all German manufacturing firms with at least 20 employees (yielding around 434,000 observations in total). It covers basic information about production value, persons employed, wages and salaries as well as details to in – and outflow of fixed assets (e.g. machines or resources). We adapt Equation 15 to estimate the elasticities for each sector i based on the data of individual firms $m = 1 \ldots n$ as follows:

$$E_{mi} = \hat{\beta}_{0,i} + \hat{\beta}_{1,i} * Y_{mi} + \hat{\beta}_{2,i} * PE_{mi}. \tag{16}$$

The overall firm-level energy use (E_{ij}) represents the sum of energetic use of different energy caries and electricity use. The price of energy (PE_{ij}) is the ratio of a firm's overall energy cost and the calculated energy use and Y_{ij} represents the gross production value of the firm. Again, ordinary least squares regression is used for estimation which leads to the following results.

The cost structure survey contains information on energy c, investments, expenses for R&D and foreign sales as well as a detailed breakdown of labor costs and wages. A total of 45% of all enterprises were surveyed, but enterprises with 500 and more employs are fully included in the survey. The estimation with firm data is done according to the NACE2 classification, which differs slightly from the classification of the national energy balance. Since these data are itself not part of the model, the results were not used directly, but instead led to re-specification of the energy demand functions to match the targeted elasticities.

[1] Research Data Center of the Federal Statistical Office and Statistical Offices of the Länder, Panel of Cost Structure Survey for years 2003–2014.

Table 2. Output and price elasticities of energy demand by industry.

Industry	Production elasticity	Price elasticity
Quarrying, other mining	0.57	−0.04
Food and tobacco	0.25	−0.06
Paper	0.51	−0.07
Basic chemicals	0.59	–
Other chemical industry	0.23	–
Rubber and plastic products	0.31	−0.07
Glass and ceramics	0.37	−0.25
Mineral processing	0.87	−0.36
Manufacture of basic metals	0.33	−0.35
Non-ferrous metals, foundries	0.50	−0.38
Metal processing	0.14	−0.09
Manufacture of machinery	0.44	−0.21
Manufacture of transp. equipment	0.31	−0.36
Other segments	0.65	−0.14

Source: Own calculations.

Table 2 shows the output and price elasticities of energy demand by industry used in PANTA RHEI because of this re-specification. An increase in paper production of 1% means e.g. for the results in section 3, that energy consumption will c.p. increase by 0.51%. If the relative price of energy inputs in the paper industry in relation to the output price for paper increases by 1%, energy demand will be reduced by 0.07%.

The similar estimates and elasticities from the estimation with firm data in Table 3 show that these estimates are robust. For the paper industry example, the elasticities are almost identical.

Table 3. Output and energy cost elasticities of energy demand by industry based on firm level data.

Industry	Production elasticity	Energy cost elasticity
Mining of coal and lignite	0.25	0.17
Mining of metal ores	0.68	−0.11
Mining support activities	0.77	−0.09
Food products	0.47	−0.12
Beverages	0.6	−0.17
Tobacco products	0.34	−0.06
Paper and paper products	0.54	−0.08
Printing and reproduction of recorded media	0.23	−0.01
Coke and refined petroleum products	0.59	0.35
Chemicals and chemical products	0.60	−0.14
Pharmaceutical products	0.36	−0.03
Rubber and plastic products	0.31	−0.06
Non-metallic mineral products	0.69	−0.37
Basic metals	0.60	−0.10
Fabricated metal products	0.33	−0.16
Machinery	0.32	0
Motor vehicles	0.45	−0.06
Other transport equipment	0.40	−0.15
Textiles	0.22	−0.08
Wearing apparel	0.12	−0.03
Leather and related products	0.17	−0.07
Wood and products of wood and cork	0.46	−0.10
Computer, electronic and optical products	0.29	−0.09
Electrical equipment	0.54	−0.25
Furniture	0.32	−0.08
Repair and installation of machinery and equipment	0.31	−0.19

Source: Estimations performed by the chair of statistics of the University of Göttingen.

For private households, consumption by purpose as heating or by fuels is already calculated in the economic part of the model in monetary terms. Additional information can be taken from stock models for transport and heating from the specific modules, as only new investments in cars, houses or appliances, or expensive insulation measures will gradually change average efficiency parameters over time.

Final demand fed_l of energy carrier l for industries can be calculated, multiplying the share of the carrier sfe_l with the overall final energy demand of the sector. For the shares, the influence of relative prices, the price of energy carrier l in relation to the sector price p_i, and of time trends are econometrically tested.

$$sfe_l = f\left(\frac{pe_l}{p_i}, t\right) \quad (17)$$

$$fed_l = sfe_l * fe_l \quad (18)$$

Energy carrier prices pe_l depend on exogenous world market prices – European import prices for gas – pw for coal, oil, and gas. Specific other price components such as energy and VAT tax rates are added. For electricity prices, different price components are explicitly modeled: Wholesale prices and margins depend on total electricity demand as a proxy for marginal costs. Other cost components such as grid costs, the EEG levy, the electricity tax, and value-added tax tr_l are extrapolated based on Prognos, Fraunhofer ISI, et al. (2021).

$$pe_k = f(pw, tr_l) \quad (19)$$

For services, households and transport-specific energy carrier prices are calculated, as for example tax rates and EEG levy partly differ strongly between end users.

For energy-related carbon emissions $ce_{i,l}$, fix carbon emission factors $cef_{i,l}$ are applied. Multiplication with final energy demand fe gives sector and energy carrier-specific emissions.

$$ce_{i,l} = cef_{i,l} * fe_{i,l} \quad (20)$$

All detailed information in the energy balance for 30 energy carriers is consistently aggregated and linked to the corresponding four industries of the IO table.

2.4. Modeling rebound effects

There are different ways to incorporate energy efficiency increases to model rebound effects resulting in different implications and interpretations. In our case, efficiency gains directly influence the impact of changes in output on energy demand: the energy efficiency term δ_i, which denotes the energy efficiency increase in industry i, enters the energy demand function multiplicatively and is limited to one of its components, the production Y_i. The average energy prices per industry PE_iresult as a weighted average of the respective energy carrier prices.

$$E_i = \hat{\beta}_{0,i} + \hat{\beta}_{1,i} * (1 - \delta_i) * Y_i + \frac{\hat{\beta}_{2,i} * PE_i}{PY_i} \quad (21)$$

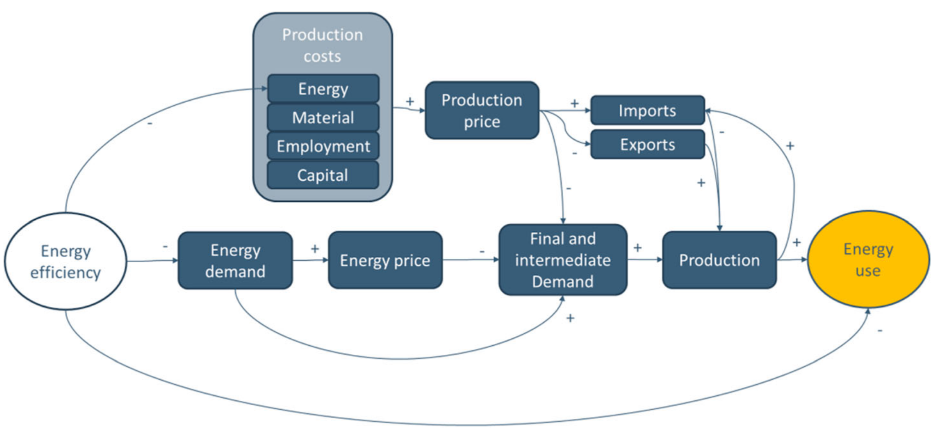
If industry i experiences an efficiency gain of e.g. 10%, the impact of the sector output on energy demand is reduced by the same amount. At first glance, it may seem surprising that the energy efficiency term does not directly influence the price component of the equation. The price of energy is influenced by the increase in energy efficiency due to decreasing demand. However, the degree to which prices react (given by the coefficient in the equation) does not change. A change in price has the same impact on energy demand before and after an efficiency increase. Note that autonomous energy demand ($\hat{\beta}_{0,i}$), which is independent of the production volume, is not influenced by the energy efficiency term, as is the impact of changes in relative prices ($\hat{\beta}_{2,i}$).

In our efficiency scenario, the overall energy efficiency increase in the industry sector is based on modeling that supports the National Energy and Climate Plan (NECP) as has been reported to the EC (EC, 2020; Prognos, Fraunhofer ISI, et al. 2021). The energy efficiency improvement starts in 2021 and ends in 2030.

In the first step, we look at an autonomous increase of energy efficiency according to Prognos, Fraunhofer ISI, et al. (2021). In 2021 the targeted decrease in energy demand starts at about 0.6% compared to the reference scenario without efficiency increase and rises to 7.4% in 2030. δ_i of the individual industry sector i is set so that a hypothetic decrease in energy demand in relative terms is the same across all industry sectors. 'Targeted decrease' is the difference between the reference development and the targeted energy demand in Figure 3. It denotes the decrease in demand ceteris paribus without any reaction of the model.

There are several channels that lead to a partly rebound of the energy demand reduction. According to Lange et al. (2019), there are three central effects at the meso and national level, which cause rebound effects: The price effect, the macroeconomic multiplier, and an increase in total factor productivity. In PANTA RHEI, mainly the price effect works, which is illustrated in detail in Figure 2. An autonomous decrease in energy inputs means a cost reduction. If the industry keeps the output price constant, profits will increase. In case of strong competition, prices will be reduced and production and demand will increase. Probably both will happen in most industries. Successful industries may increase investment in the future and their employees might ask for higher wages. Price changes will also affect demand by other industries and by final consumers. At the same time, input costs in

Figure 2. Rebound effects due to energy efficiency improvement.



other industries will be reduced and consumers can save money and redirect part of their consumption.

Energy markets can also be affected. Reduced demand for energy can reduce the domestic price of energy carriers with impacts on the demand of other consumers. Their demand will increase if it is price dependent. Effects on international energy markets should be small at least for oil and gas with international or even global markets, because Germany is only a small country in terms of global energy demand. A smaller reduction in German demand for coal, oil or gas has only a small effect on the international prices. Effects could be higher for the European electricity market, which is interconnected. But as the wholesale price only makes small part of electricity end-user prices in Germany (less than 20% for consumer prices), effects are also limited.

Finally, there will be some changes on the macroeconomic level, as the German economy will be more competitive. Exports could be higher and imports lower than before (if other countries do not imitate the energy efficiency improvement of German industries). German consumers can spend more. Due to all these adjustments of prices and volumes, energy demand will be higher than expected due to the autonomous increase in energy efficiency.

Given the reactions of the model, the actual decrease in energy demand differs from the targeted decrease. This relative difference between observed and hypothetical decrease can be interpreted as the rebound effect (θ_i).

$$\theta_i = 1 - \left(\frac{\frac{E_i^{actual}}{E_i^{reference}} - 1}{\frac{E_i^{targeted}}{E_i^{reference}} - 1} \right) \tag{22}$$

3. Results: rebound effects in PANTA RHEI

3.1. Rebound effects

The mesoeconomic rebound effect across all industries is between 7% in 2021 and 12% in 2030 (Figure 4). This means that instead of the targeted 7.4% decrease in overall energy consumption in 2030 the actual decrease will only be 6.5%. The macroeconomic rebound effect at the economy level lies between 12% and 18% during the observed period, both increasing over time. Figure 3 shows targeted (green) and actual (red) energy demand of the whole economy in the efficiency scenario, compared to a reference scenario without efficiency measures (gray). The red area represents the rebound effect.

The magnitude of the mesoeconomic rebound effect differs for individual industries. As depicted in Figure 4, the effect takes on values of about 1% in certain industries at the beginning of the observed period (Quarrying, other mining; basic chemicals) to up to 20% at the end of the period (metal processing, manufacturing of transport equipment). The sector with the smallest rebound effects, both in the short and medium term is other chemical industry (0% in 2021, 3% in 2030).

Consistent with other research, the magnitude of the rebound effect correlates with the price elasticity of energy demand of a specific industry. As Figure 5 shows, this holds especially true at the beginning of the observation period (sectors with a price elasticity of zero are omitted). Glass and ceramics, mineral processing, basic metals, non-ferrous metals,

Figure 3. Targeted and actual energy demand in the efficiency scenario compared to reference in Germany.

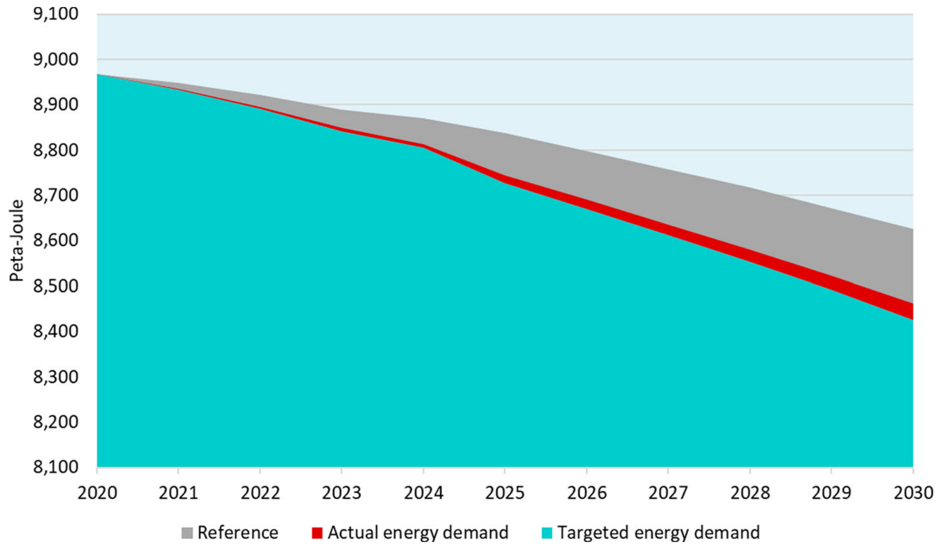
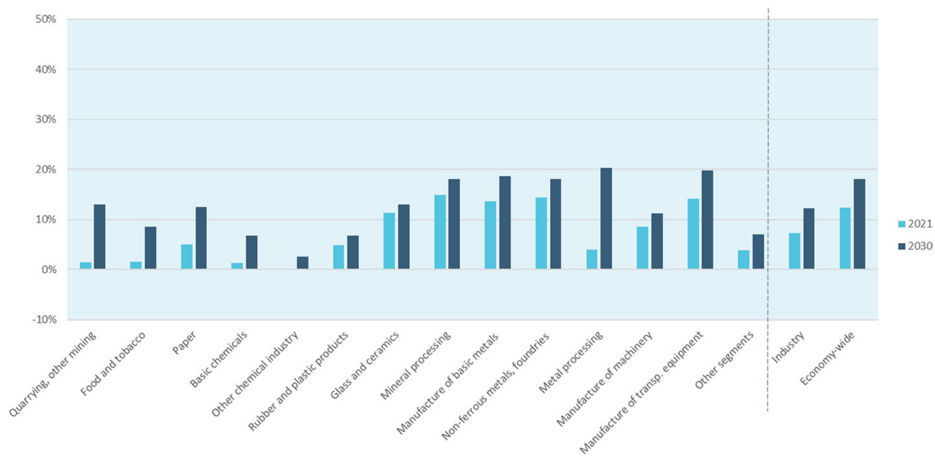


Figure 4. Rebound effects by industry – start and end of observation period.



machinery, and transport equipment are industries with higher price elasticities according to Table 3. Figure 4 also shows that the economy-wide effect is larger than the effect in industry. Price reduction due to higher energy efficiency induces higher energy demand in other sectors of the economy such as private households, transport, and services (Figure 6).

3.2. Macroeconomic effects

The increase in energy efficiency has a small positive impact on overall economic development. In 2030, GDP in constant prices lies about 0.2% higher in the efficiency scenario compared to the reference case. One reason for the rather low value compared to the effects

Figure 5. Magnitude of the rebound effect and price elasticity of energy demand by industry, efficiency scenario (Bubble size indicates final energy demand).

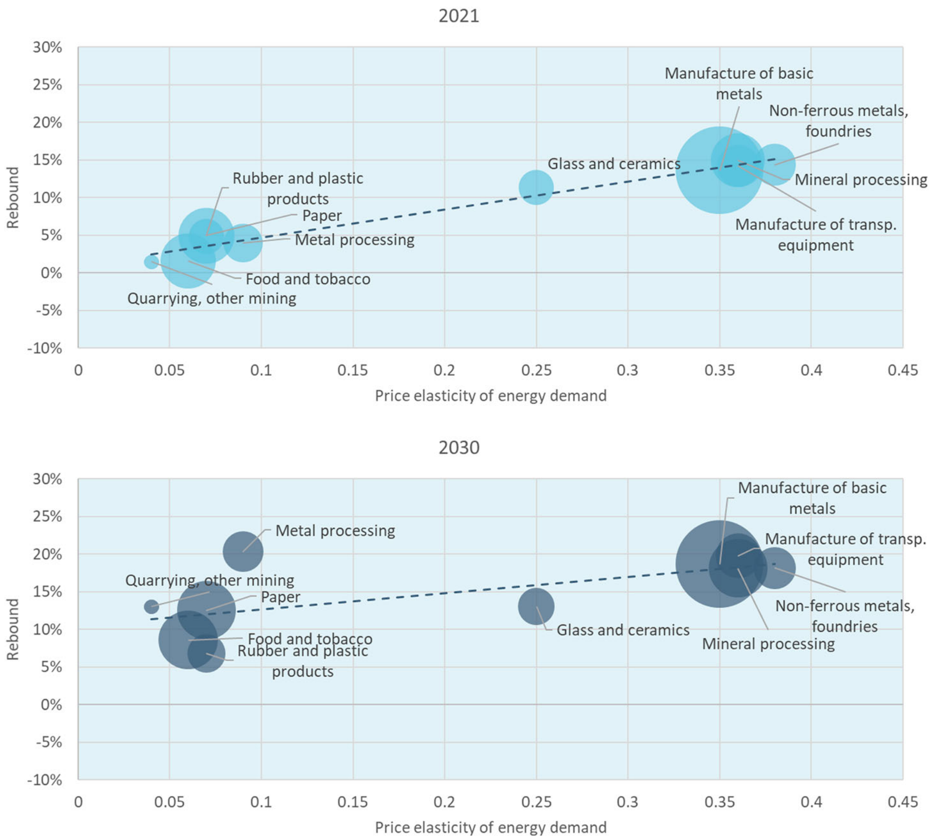
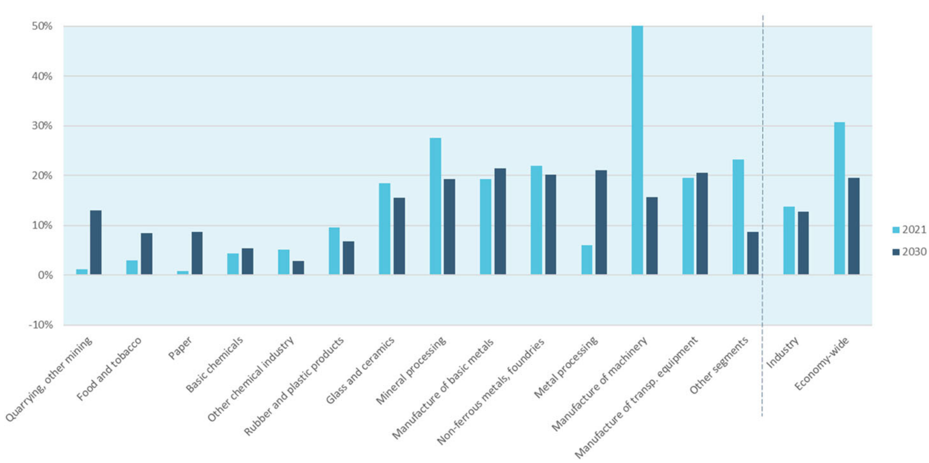


Figure 6. Rebound effects by industry, investment scenario.



shown in Table 1 is the limitation of the efficiency increase to industry sectors. Secondly, the rebound effects in PANTA RHEI are also at the lower end of the reported range. Finally, energy prices in Germany are high in international comparison and are strongly characterized by administrative price components. Efficiency increases therefore only have a limited effect on user prices.

Given this low increase in economic activity, it can be concluded that mainly price changes lead to the rebound effects. As a result of falling demand for energy, prices decline, so that demand for energy goods increases in other sectors. But the overall economic production quantity increases only to a limited extent as a result, so the quantity effect on energy demand remains limited.

Since an autonomous increase in energy efficiency can be regarded as a rather strong assumption with potentially high impact on the results, as a next step a sensitivity is considered in which energy efficiency increase in manufacturing is accompanied by an increase in investment (from here on 'investment scenario'). The increase in energy efficiency and the ceteris paribus decrease in energy consumption is modeled as in the case described above.

When calculating the costs for the energy efficiency improvement, the ratio of physical energy unit saved per Euro spent is assumed to be constant over industries, while varying over time, and again follows the findings of Prognos, Fraunhofer ISI, et al. (2021). Additional investments start in 2020 (one year before efficiency gain takes place in 2021) and continues until 2030. While the rebound effect is increasing over time in the autonomous efficiency scenario on the industry level as well as economy wide, we now find the rebound effect to be slightly decreasing over time, with higher effects in the early years of the observation period. The industry rebound is about 14% in 2021, and lies at 13% in 2030, only being slightly higher than the industry rebound in the autonomous efficiency scenario. The economy-wide rebound is initially around 31% and reaches a value of 19% in 2030. The decline of the rebound effects over time can be explained by the modeling of investments. Additional investment in energy efficiency increases the capital stock. If demand increases only to a limited extent, the endogenously determined investments increase less than in the reference, according to Equation 5.

The inclusion of (additional) investment necessary for the energy efficiency improvement as a first sensitivity increases the short-term rebound effect. As machinery delivers big part of the more efficient equipment, the rebound in this industry reaches 50% in 2021, as sector production increases. In the autonomous efficiency scenario, industry sectors react uniformly in the way that in all cases initial rebounds are low, increasing over time. In the investment scenario, this still holds true for about half of the sectors, while others show declining rebound effects. The results suggest that even with assuming necessary additional investment in energy efficiency, its medium-term effect on the rebound effect on an industry level is small and energy demand in 2030 is roughly the same for both, the autonomous efficiency scenario, and the investment scenario.

As noted above, PANTA RHEI does not react as strongly to changes in prices as do many CGE models analyzing rebound effects. Price elasticities of different components of demand are estimated and found to significant for only part of the relations, especially for many intermediate inputs no price influence could be detected. As a second sensitivity analysis, the model was thus modified to incorporate some of the respective substitution channels from CGE models to increase reaction to price changes in manufacturing. All non-energy intermediate input coefficients are now dependent on changes in relative prices of the respective input sector compared to all other prices, with an assumed elasticity of 0.5.

The approach resembles input factor substitution in nested production functions. Exports now directly react to changes in the relation of sectoral production prices and import prices, as do imports. The corresponding elasticities are assumed to be 1 for exports and 0.2 for imports. In this scenario, the industry wide rebound is about 15%, while the economy wide rebound increases to 21% in 2030 (against 12% and 18% in the main scenario). This means that assuming higher price elasticities (in this sensitivity analysis) increases rebound effects in industry and on macroeconomic level.

4. Conclusions

The presented results confirm the existence of meso- and macroeconomic rebound effects in Germany. Energy efficiency improvements in manufacturing induce impacts that reduce the theoretical energy reduction due to rebound effects caused by the energy efficiency increase. The rebound effect is a kind of air resistance in the economy. It reduces the intended decoupling of economic activity and energy use. Rebound effects are positively related to the high-price elasticities of sectoral energy demand. Higher elasticities of substitution for intermediate inputs and production factors will also increase rebound effects. Considering additional investment needed for higher energy efficiency leads to an additional short-term rebound effect in industries such as machinery that deliver this equipment.

Macroeconomic rebound effects of autonomous energy efficiency improvement in manufacturing amount to 12% in 2030. On sector level, the mesoeconomic effects range between close to 0 and almost 20%. Economy-wide rebound effects reach 18% in 2030. Two sensitivity analyses show that assumptions about additional investments needs of energy efficiency or easier substitution between intermediate inputs can increase the effects up to 15% for the industry wide effect and 21% for the economy-wide rebounds. This must be placed in the policy and market context. According to the agreement between the German government and German industry to increase energy efficiency of August 1, 2012, the German manufacturing industry agrees to the introduction of Environmental Management Systems (EMAS) or audits in companies applying for peak compensation of energy taxes to determine measures to increase energy efficiency, among others as part of a cost–benefit analysis (RWI, 2019). In this agreement, the German manufacturing industry has promised to increase energy efficiency from 2013 onwards, which is monitored annually. This commitment may partly explain lower rebound effects in German industry compared to other countries. In international comparison, German energy markets are additionally characterized by high administrative prices. A decline in energy demand therefore tends to lead to lower price effects in an international comparison, as part of end-user prices is fix, which limits rebound effects.

The results of our modeling are consistent with the literature, even if the effects are below average. While macroeconometric models report rather low economy-wide rebound effects in the range of 10–25%, CGE models tend to report effects in the range of 50% and above. According to Brockway et al. (2021) more than half of the energy efficiency improvement could be eroded by rebound effects. Colmenares et al. (2020) report a medium energy rebound effect of 42.5% for economy-wide ex-ante simulation studies on the producer side. This has to do with the different characteristics of the models. The more flexible the production structures are modeled, i.e. the greater the substitution possibilities between inputs and the longer the observation period, the higher the rebound effects. Assumptions about price elasticities in industries play a central role, which are lower in PANTA RHEI compared to CGE applications. Also, macroeconomic multiplier and the effects of an increase in total factor productivity are more pronounced in a CGE model than in PANTA RHEI. The conclusion of many analyses with CGE models that energy efficiency policies are largely ineffective due to rebound effects is therefore less reflected in macroeconometric models. However, a look at German energy efficiency policy as described above also shows that the rebound effects in German industry are probably smaller than in other countries.

Nevertheless, technology-driven efficiency programs must take rebound effects into account according to our modeling. This can be in the form of a reduction of expected effects, for example, 20% to build on our results for German manufacturing, to take account of rebound effects triggered by policy measures and to ensure that energy efficiency targets are met. Price instruments and emission caps can probably also reduce rebound effects.

Given the need for the global economy to become largely climate neutral to limit global warming to below 1.5° if possible, as agreed in the Paris Climate Agreement, and the far-reaching GHG reduction targets, the magnitude of rebound effects helps determine how ambitious climate mitigation strategies need to be. Germany, for example, has committed to becoming climate neutral by 2045. In first scenarios on the possible achievement of the target (Prognos, Öko-Institut, et al. 2021), rebound effects are not yet considered. This will have to be different when choosing the appropriate and necessary policy measures. In the future, these measures must always be considered together with the rebound effects and the target of GHG neutrality. The magnitude of rebound effects and the ability to limit them through smart policies will also determine what room remains for future economic growth while limiting global warming. This could mean exploring new mitigation pathways such as degrowth scenarios on global level (Keyßer & Lenzen, 2021).

As a next research step, other policies will be tested in PANTA RHEI that might further reduce the identified rebound effects. Due to the role of prices higher carbon or energy prices in industries, emission caps but also public funding for energy efficiency measures, which plays an important role in German energy efficiency policy and additional investment requirements for these industries should be considered. Behavioral changes, which have so far only been considered to a limited extent in modeling, are becoming increasingly important (Keyßer & Lenzen, 2021).

A second aspect of future research is a better inclusion of resource aspects and different sources of energy in modeling studies. Resource inputs (materials) are often neglected, but the use of resources could also be affected by rebound effects or energy efficiency improvement could induce additional resource use, that is not explicitly modeled. Another difficulty for addressing rebound effects in future impact assessments is the partly desired shift to carbon neutral energy sources, for example, in the production of steel using green hydrogen or in electricity generation. New carbon free production processes partly need huge amounts of electricity. A rebound effect in the form of lower energy efficiency will thus be implicitly aspired by policy measures such as carbon prices, as they make carbon free, but energy-intensive processes more competitive. This will pose an additional challenge to ex-ante modeling the rebound effect of energy efficiency improvement and to respective climate policies.

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