

Rebound Effects of Behavioural Efficiency Improvements in Households' Energy Services Consumption in the Presence of Demand Rigidities and Habits

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Abstract

Changes in energy consumption behaviour of households are recognised as a main contributor to reduced energy demand in developed countries. We investigate the economy-wide impacts of a more efficient electricity consumption behaviour in the presence of demand rigidities and consumption habits. Our findings demonstrate that in the context of energy efficiency improvements in households, taking into account rebound effects is vital, as rebound effects can drastically reduce expected energy savings. We further point out that policies aimed at reducing household energy consumption should always take demand rigidities and consumption habits into account, otherwise rebound effects could be significantly underestimated.

JEL Classification

D13; D58; Q41; Q43

Keywords

Rebound; demand rigidities; energy service consumption; consumption habits

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1 Introduction

Changes in energy consumption behaviour of households that lead to a higher energy-efficiency offer considerable promise for reducing financial cost and environmental damages associated with energy use. However, if households adjusted their consumption patterns, some of these efficiency gains could disappear due to increases in other energy consumption. This process is also known as *rebound effect* (Chan and Gillingham, 2015). The aim of this paper is to shed light on the importance of taking into account households consumption particularities when analysing this effect.

There is a huge body of literature that discusses the rebound effect. A useful overview of the rebound literature can be found in, for example, Colmenares et al. (2018), Turner (2013) and Sorrell (2007). There are many different estimates of the rebound effect, with most studies suggesting that rebound is not a negligible side effect (see e.g. Lemoine, 2020, Gillingham et al., 2016, Sorrell et al., 2009). It is apparent from the literature that the numerical determination of the rebound effect is associated with some difficulties and crucially depends on the context of the investigation. The literature on economy-wide impacts of energy efficiency improvements has so far focused mainly on the production side (see e.g. Lemoine, 2020, Koesler et al., 2016, Turner and Hanley, 2011).

There is only a small number of studies on the economy-wide effects of an efficiency improvement of households. Fullerton and Ta (2020) compare rebound effects from a costless technology shock to those from a costly energy efficiency mandate and decompose each total effect on the use of energy into components that include a direct efficiency effect, direct rebound effect, and indirect rebound effect. Lecca et al. (2014) provide a clear approach of how to measure rebound both at the economy-wide level as well as on the household level and investigate the impact of an efficiency improvement in the use of energy in UK household energy service consumption. Figus et al. (2018) are interested in the wider implications of vehicle-augmenting efficiency improvements. They model private transport consumption as a household's self-produced commodity formed by a vehicle and fuel use in computable general equilibrium (CGE) simulations in order to investigate the wider implications of efficiency improvements on the system-wide change in fuel use when prices and income are endogenous. The only study that looks at households' consumption particularities in combination with rebound effects is Koesler (2013) who investigates the rebound effects of an efficiency shock in the provision of private transportation in the presence of habits in consumption.

Building on the theoretical consideration concerning consumption habits outlined

in [Koesler \(2013\)](#), this paper uses a CGE model with a more realistic energy service consumption structure to shed light on the importance of considering household consumption particularities in the electricity consumption of households. In particular, the model takes into account that the energy service consumption behaviour of households may be governed by demand rigidities and energy service consumption habits that implicitly affect consumption. In contrast to [Koesler \(2013\)](#), who implements the same habit in every sector and region, we focus on the impact of energy service consumption habits and demand rigidities to investigate how a behavioural efficiency improvement in households affects the different rebound areas of the economy. We further disaggregate the world input output database (WIOD) energy consumption data to separate the electricity consumption data and complement the CGE model with an explicit modelling of an electric appliance stocks. This allows us to shift the focus from private transportation to electricity consumption habits and demand rigidities of households, which has to date not been studied in the rebound literature.

The paper contributes to the existing literature in several ways. We provide further evidence that rebound effects have the potential to significantly reduce the expected energy savings of behavioural energy efficiency improvements using the example of electricity consumption of German households. By implementing energy service consumption habits and demand rigidities in the analysis, we shed light on the importance of consumer-specific particularities that influence energy service consumption. Through the implementation of demand rigidities in the analysis we show how important it is to consider the different rebound areas and that energy service consumption rebounds are limited.

The paper is structured as follows. In the next section, we introduce a stylised model that includes an energy service consumption habit and give a description of our rebound measure. After that we apply the mechanism in a more general setting and investigate the rebound effect on the basis of a CGE model. Finally, we summarise our results and conclude.

2 Theoretical Considerations

Before we generalise the structure and turn to a more comprehensive setting to investigate the impacts of energy service consumption habits and demand rigidities on the rebound effects that result from a behavioural efficiency improvement, we present a stylised version of this model and give a description of the rebound effects we are going to analyse.

The model consists of a representative household, an energy service and another good that are used for final consumption. It further features two intermediate commodities used by the households to produce the final consumption goods. The distinction between the consumption goods and the commodities in the consumption structure is an important modelling aspect, as households rarely actually consume commodities, such as light bulbs and electricity or a heater and fuel, but combine these to form a service they consume such as energy or transport services. Therefore, there are also substitution possibilities within the consumption of energy services, which have to be considered in the modelling. The energy efficiency increase that potentially triggers rebound ultimately takes place at the energy service consumption level and makes the energy input more productive.

2.1 Theoretical Model

In the model, utility of the representative household is given by utility function U that includes an energy service and another consumption good. Furthermore, we add consumption habits to the energy service consumption. We follow [Koesler \(2013\)](#) and include an energy service habit in the household problem. To achieve that we extend a Cobb-Douglas utility function with a term that can be interpreted as some form of necessary consumption. It results from the energy service consumption level in the previous period and relates the current energy service consumption decisions to it. In our model, we assume that only the energy service consumption is affected by the habit. Hence, the utility of the household at time t is given by:

$$U_t(s_t, s_{t-1}, z_t) = (s_t - \theta_s s_{t-1})^{\alpha_u} (z_t)^{\beta_u}, \text{ with } \alpha_u + \beta_u = 1. \quad (1)$$

where s_t gives the amount of the energy service and z_t the amount of another consumption good that are consumed by the household in period t . The corresponding expenditure shares are given by α_u and β_u . The strength of the persistence of past consumption or, in other words, the strength of the habituation is given by θ_s , with $\theta_s < 1$. Note that for simplicity we limit the habituation to one period, but it is straightforward that extending the range of habits has the same effect as increasing θ_s . Households face a budget constraint of the form $M = p_s s + p_z z$, where p_s and p_z are the prices for the energy service and the other consumer good, respectively. We assume that households have a fix income M which is not influenced by the efficiency change.

If households take past consumption as given, demand for energy service s in period t by households is given by:

$$s(p_s, p_z, s_{t-1}, M) = \frac{\beta_u}{p_s} M + \alpha_u \theta_s s_{t-1}. \quad (2)$$

The demand for energy service s in period t positively depends on the strength of the energy service consumption habit θ_s . A strong habit θ_s in energy service consumption of the previous period s_{t-1} leads to a greater demand for energy services in the current period.

As households do not consume energy but energy services, we model the energy service, which is formed combining energy and energy using appliances. Accordingly, energy service consumption s can be described by a constant elasticity of substitution (CES) function:

$$s(x, e) = \left(\alpha_s x^{\frac{\sigma-1}{\sigma}} + \beta_s (\gamma e)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}. \quad (3)$$

The good x and energy e are the intermediate goods that are required in the consumption of the energy service s . The degree of energy efficiency in consumption is given by γ , which is assumed to equal one in the initial state. The elasticity of substitution σ gives the substitutability between intermediate inputs and the respective input shares are given by α_s and β_s .

The resulting demand for energy e for the consumption of energy service s is given by:

$$e(s) = \left(\frac{\beta_s \gamma^{\frac{\sigma-1}{\sigma}}}{p_e} \right)^{\sigma} \left(\alpha_s^{\sigma} p_x^{1-\sigma} + \left(\beta_s \gamma^{\frac{\sigma-1}{\sigma}} \right)^{\sigma} p_e^{1-\sigma} \right)^{\frac{\sigma}{1-\sigma}} s. \quad (4)$$

To see how the habit affects the energy demand and thereby also the rebound effect we combine Equation (2) with Equation (4) to get the demand for energy e of the representative household for s at time t :

$$e = \left(\frac{\beta_s \gamma^{\frac{\sigma-1}{\sigma}}}{p_e} \right)^{\sigma} \left(\alpha_s^{\sigma} p_x^{1-\sigma} + \left(\beta_s \gamma^{\frac{\sigma-1}{\sigma}} \right)^{\sigma} p_e^{1-\sigma} \right)^{\frac{\sigma}{1-\sigma}} \left(\frac{\beta_u}{p_s} M + \alpha_u \theta_s s_{t-1} \right). \quad (5)$$

Notice that we omit the time indices if it is the current period.

From Equation (5) it can be directly seen that the strength of the habit θ_s can significantly influence consumption in the following period. The resulting rebound effects from an efficiency improvement of γ will therefore also depend on the strength of the habit and the consumption of the energy service in the previous period s_{t-1} .

2.2 Energy Efficiency Rebound Effect

The energy efficiency rebound describes a situation in which expected gains from an efficiency improvement of an energy input, which can be caused by a new technology or an adapted behaviour, are reduced by an increase in the use of this input following the efficiency improvement. In our small stylised example, the rebound effect leads to a change in the amount of energy e used in the consumption of the energy service resulting from a change in the efficiency γ . However, to investigate impact of the efficiency improvement on total energy usage we have to consider all rebound channels.

The literature on rebound effects regularly distinguishes between direct, indirect and economy-wide rebound (see e.g. [Sorrell and Dimitropoulos \(2008\)](#)). In this paper we only provide a brief explanation of the direct and indirect rebound and focus on the investigation of the economy-wide energy rebound, households' total energy rebound and households' energy service energy rebound in the presence of household habits and demand rigidities.

The direct rebound effect results when efficiency improvements in the consumption of an energy service lead to a decrease in the effective price of that energy service. This will lead to an increase in the demand for the energy service. Consequently, this results in a higher demand for the intermediate input energy which is required to cover the additional demand. As we will see in our simulations, the direct rebound effect is strongly related to the choice of elasticity of substitution in parametrisation of the energy service consumption.

If the elasticity of substitution is $\sigma < 1$, households are having difficulties in substituting for the more efficient energy input which results in a lower energy intensity. A high substitutability of $\sigma > 1$ leads to a situation in which consumers of energy services are using more energy in relative terms. If $\sigma = 1$, which implies a Cobb-Douglas consumption function in which input intensities are constant, energy intensity remains constant.

The indirect rebound effect describes a situation in which a reduction of the effective price of the energy service resulting from the more efficient consumption of the energy service also relaxes the consumers' budget constraint ([Sorrell and Dimitropoulos, 2008](#)). This income effect allows households to demand more from other products and services and opens an additional channel for the rebound effect. Depending on the substitutability in consumption, this effect can lead to considerable shifts of the rebound effect to other sectors.

The economy-wide rebound effect can result in an increase in the energy use of other related sectors and can also counter the benefits of the energy efficiency change. It describes the rebound that is happening on the economy-wide level, in a setting where all prices and quantities are free to adjust and the efficiency improvement leads to a series of secondary price and quantity adjustments that take place in connected sectors. To take all these price and quantity adjustments into account, it will be necessary to utilise a CGE model that includes the main elements of our stylised model.

When interpreting efficiency changes, we measure the changes in natural units, which means that if all other things remain unchanged, a 10% efficiency increase of an input will result in a 10% decrease of the input usage. We build on the work of [Lecca et al. \(2014\)](#) and measure rebound on the basis of the relationship between changes in the use of energy and the proportional change in energy efficiency. As in the CGE model all prices and quantities are free to adjust, the rebound effect can be investigated for different areas of interest. Our CGE rebound measure is given by

$$Rebound_s = \left(1 + \frac{\Delta E_s}{\left(\frac{E_a}{E_s} \right) \Delta \gamma_a} \right) \cdot 100, \quad (6)$$

where s is the scope and a the activity where the efficiency change takes place. E_s is the energy use in scope s , whereas E_a is energy use of activity a . The change in energy use within the scope s is given by ΔE_s . The change in efficiency taking place in activity a is given by $\Delta \gamma_a$. As we will focus on a behavioural energy efficiency improvement in the consumption of electricity using energy services of households, we consider three scopes in our analysis: The rebound of electricity use in energy service consumption, the rebound in household energy consumption and the rebound in economy-wide energy consumption.

The differentiation between different occurrences of the rebound effect will become interesting when we compare the different scenarios, in particular when we consider cases in which rebound channels are blocked due to demand rigidities.

3 Numerical Illustration

In this section, we will explore the rebound effect in a more comprehensive CGE model that includes the main elements of the stylised example of the previous

section. As we are interested in the impacts of habits and demand rigidities on energy service consumption and rebounds, we complement the utility function and energy services consumption structure with habits and a more realistic energy capital good that features a demand rigidity. The analysis we will be focused on energy service consumption that use electricity as the energy input as it is a very important energy good in households consumption that also features habits.

3.1 Model Description

We utilise the WIOD CGE model (Koesler and Pothén, 2013), which is a static, multi-sector, multi-regional CGE model which is calibrated on data from the World Input-Output Database (WIOD) (Timmer et al., 2015). The underlying production functions are modelled using nested constant elasticity of substitution production functions that exhibit constant returns to scale. The production functions consist of three nests to specify the substitution possibilities between capital K , labour L and intermediate goods x of region r .

We apply a KLEM production structure, where capital and labour enter the production function on the lowest level. On the second level, value added is combined with energy. On the top level of the CES function the energy-value-added composite is combined with a non-energy material aggregate. Goods can be produced from $x_{(eg)}$ units of carbon-emitting energy inputs, and $x_{(i)}$ units of non-energy intermediate goods. These goods can be used for final consumption and intermediate use production activities.

Intermediate goods are so-called Armington aggregates, i.e. they consist of a combination of domestic and foreign inputs, which allows us to model goods from different origins as imperfect substitutes with different substitutability between domestic and foreign output, and between different foreign regions (Armington, 1969). We further assume perfect competition in all markets. This production structure is displayed in Figure 1.

Final demand in region r is given by a representative household who maximises its utility by spending her budget on consumption goods. Households are endowed with a fixed amount of labour and capital, which is mobile across sectors within regions but not across regions. The representative household's budget is determined by the consumer's income from selling these factor endowments on the market and from possible government transfers.

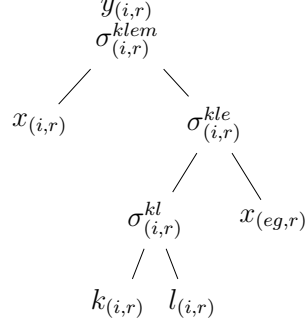


Figure 1: KLEM Production Function

3.1.1 Energy Service Consumption

We extend the model by an energy service module that describes the consumption of energy services as described in our theoretical model in Section 2.1. Accordingly, energy service consumption in region r is described by:

$$s(x_{(a)}, x_{(el)}) = \left[\alpha_{(a)} x_{(a)}^{\frac{\sigma^{ela}-1}{\sigma^{ela}}} + \alpha_{(el)} (\gamma_{(el)} x_{(el)})^{\frac{\sigma^{ela}-1}{\sigma^{ela}}} \right]^{\frac{\sigma^{ela}}{\sigma^{ela}-1}}, \quad (7)$$

where $x_{(el)}$ is the amount of electricity input in households' energy service consumption that is combined with $x_{(a)}$ units of electric appliances in region r . As before, the degree of substitutability in the consumption of the energy service is given by the elasticities of substitution σ^{ela} . Share parameters are given by $\alpha_{(el)}$ and $\alpha_{(a)}$.

The exogenous parameter $\gamma_{(el)}$ is an input productivity parameter, which can be thought of as some form of *behavioural efficiency* that describes the level of energy efficiency and is normalised to one in the benchmark. In our simulations, we increase the behavioural efficiency by 10% to investigate the impact of a more efficient consumption behaviour. Behavioural inefficiencies in energy service consumption can have various non-technical reasons. Households could be lazy or might for example possess only imperfect knowledge about how goods are most efficiently used in energy service consumption. Energy services might be consumed more efficient without switching to a more efficient technology. Habits that lead to an unnecessary high energy consumption are for example heating a room with open windows, taking a shower without turning off the water when soaping or not switching off appliances instead of using the standby mode.

As we are interested in the effects of a change in the efficiency of energy service consumption, we extend the utility function to feature a distinction between energy services on the one hand and other consumption goods on the other hand as described in our theoretical model in the previous section. The household's utility function depicting her preferences over various bundles of goods is a nested CES function that aggregates the consumer's expenditure on non-electricity composite goods that are formed by combining non-electricity energy goods $x_{(eg)}$ and non-energy goods $x_{(i)}$ at the bottom level and the energy service s that enters at the top level. Utility of the representative household in region r is given by:

$$u(s, x_{(eg)}, x_{(i)}) = \left[\alpha_{(s)} s^{\frac{\sigma^{sz}-1}{\sigma^{sz}}} + \left(\alpha_{(eg)} x_{(eg)}^{\frac{\sigma^{egi}-1}{\sigma^{egi}}} + \alpha_{(i)} x_{(i)}^{\frac{\sigma^{egi}-1}{\sigma^{egi}}} \right)^{\frac{1-\frac{1}{\sigma^{sz}}}{1-\frac{1}{\sigma^{egi}}}} \right]^{\frac{\sigma^{sz}}{\sigma^{sz}-1}} \quad (8)$$

3.1.2 Habits in Energy Service Consumption

We further complement a habit formation process in the utility function similar to the one described in Section 2.1. If household have habits, they adjust only a share of their consumption bundle to the current situation and the other share is determined by their habits. Households must always consume at least $\theta^s s_{(t-1)}$ of energy services consumed in the previous period. Accordingly, energy service consumption is given by:

$$s = s_{(t)} - \theta^s s_{(t-1)}. \quad (9)$$

Household habits are formed on the basis of the consumption bundle of the previous period and thus a change in a consumption decision will be quickly incorporated in household habits. The direct interdependence between current consumption and habits results in an adaptation process, where current consumption and habits are adjusted period for period until a situation is reached, where current consumption equals household habits.

Following the notation of the theoretical model presented before, θ^s determines the degree of habit persistence in energy service consumption. Share parameters are given by $\alpha_{(s)}$, $\alpha_{(eg)}$, $\alpha_{(i)}$. Substitutability in consumption between energy services and other consumption goods and between energy and non-energy goods is given

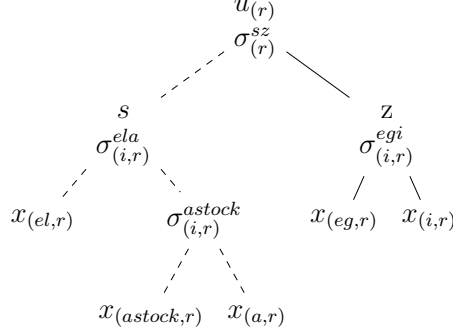


Figure 2: Household Consumption Structure

by the respective substitution elasticities σ^{sz} and σ^{egi} . The structure of the utility function is shown in Figure 2.

3.1.3 Demand Rigidities in Energy Service Consumption

The dashed lines indicate the new branches we added to the WIOD CGE model in order to incorporate the energy service consumption. We complement the CGE model with an existing appliance stock by applying standard depreciation rules assuming an average durability of 10 years over electric appliances in the household. New purchases of electrical appliances are combined with the existing appliance stock $x_{(astock)}$, assuming perfect substitutability. By doing so we give a more realistic consumption structure and share parameters. Without implementing the stock, the share of electricity in energy service consumption would have been overstated, leading to higher rebound levels.

We further incorporate an energy service demand rigidity in our simulations that will restrict the purchases of new appliances, such that the appliances level is limited to its benchmark level. The demand rigidity in energy service consumption is due to the fact that households might not be able to switch their electric appliances in the short run. This can be due to several reasons like financial constraints, opportunity costs or other factors. The demand rigidity prevents the household from substituting the capital good without restrictions and might limit energy service rebound effects in the short run.

As we will show in the next section, existing electric appliances represents a non-negligible part of energy service consumption that cannot simply be replaced overnight. Therefore, the implementation of demand rigidities is a very important feature when we consider the different rebound channels in our simulations,

as the energy service rebound channel will be blocked by the demand rigidity. This can lead to situations where other rebound channels and therefore other sectors are more affected by the change in behavioural efficiency, which can have far-reaching consequences. Demand rigidities can prevent energy efficiency investments from taking place, with counterproductive consequences for energy saving policies and related policy measures.

The demand rigidity is the final component of our energy service modelling and show the importance of implementing all these specifications into the model, since the rebound effect is significantly influenced by the particularities in households' energy service consumption.

3.2 Data and Energy Service Calibration

The CGE model calibrated using the World Input-Output Database ([Timmer et al., 2015](#)). With regard to the general economic structure, energy use and CO₂ emissions, the model is calibrated to the year 2009. We change the original aggregation structure of the basic WIOD CGE reduce the sectoral disaggregation to 13 sectors and three regions (Germany, EU and a rest of the world region), as we are mainly interested in the impacts on energy service consumption in Germany. For our analysis, we focus on the effects within Germany and abstract from interregional effects. The aggregation scheme is displayed in Table A.1 and Table A.2 in Appendix A.1.

To be able to draw conclusions regarding the specific energy demand changes and rebound, the sectoral data was disaggregated such that it allows to explicitly model the energy service consumption. To account for the electric energy service consumption, we follow the approach of [Baikowski \(2018\)](#). We use the region specific consumption data from WIOD and use the fact that all final demand goods from the sectors *machinery* (*MACH*) and *electrical equipment* (*ELEQ*) are using electricity as their main input. Our strategy for modelling energy service consumption is that the household combines these electricity using goods with electricity to form generate the energy service good the household consumes, which allows us to account for substitution between those intermediate inputs. In 2009, the annual consumption of electric appliances accounts for about 3.3% of the household's consumption expenditure, but only includes those goods that are newly purchased. Including imports, the total value of the yearly purchases of electric appliances in 2009 amounts to 56 billion US\$.

Two components are however missing in the WIOD data. The appliance stock and the data on electricity consumption. To account for good stocks of electric

appliances, we use the data from [Federal Statistical Office Germany \(2011\)](#). The study states an average lifetime of these goods between 5 and 16 years, with larger devices having a longer lifetime. According to [Federal Statistical Office Germany \(2011\)](#) the total value of the electrical appliances stock that we consider in our analysis in Germany amounts to about 185 billion US\$, which is in line with the WIOD data assuming a depreciation over 10 years with a depreciation and replacement rate of 10%. The electric appliance stocks are used to calibrate a more appropriate share parameter in the energy service consumption function. We assume perfect substitutability between these stocks and new purchases of electric appliances.

To account for electricity consumption of households, we disaggregate the *electricity gas and water supply* sector (*ELGW*) in the WIOD data for this case. As WIOD does not provide the necessary prices and quantities we use the consumption data from [AGEB \(2012\)](#) and price data from [BDEW \(2017\)](#) to separate electricity, gas and water from the single value given in the original WIOD dataset. This last disaggregation allows us to explicitly model the electricity consumption of households which we combine with the electric appliances and electric appliance stock as displayed in Figure 2.

The elasticities of substitution used in the CGE model are taken from [Koesler and Schymura \(2012\)](#) who estimated substitution elasticities for all sectors included in the database. Armington elasticities are taken from GTAP8 ([Hertel et al., 2014](#)) and mapped to the respective sectors.

The model distinguishes between energy related CO₂ emissions (arising due to the burning of fossil fuels) and process emissions (e.g. caused during the production of cement). Emissions are modelled as a fictive necessary input into the production of commodities and consumption goods that is paired with the input causing the emission in a Leontief nest in the respective production function. The shares of the fictive inputs vary depending on the type of accompanied energy good.

3.3 Scenario Description

In this subsection, we distinguish between a set of different scenarios to account for sensitivity with respect to the most important parameters in energy service consumption. In all scenarios, the exogenous productivity parameter $\gamma_{(el)}$ that describes the level of behavioural energy efficiency will be increased by 10%. As described before, the energy services might be consumed more efficient without switching to a more efficient technology, which could lead to a lower energy consumption and become a new habit eventually.

Table 1: Overview of the Main Scenarios

Short	Description	Habit (θ^s)	Demand rigidity
NO-HAB	no habit persistence	-	no
HAB-DR*	households have consumption habits	0.1 - 0.5	yes
HAB*	households have consumption habits	0.1 - 0.5	no

*We increase the habit stepwise by 0.1.

Other important parameter are the degree of demand persistence, respectively, the strength of the habit (θ^s), the substitution possibilities between energy services and non energy related household consumption (σ^{sz}) and the possibility to substitute energy with energy service material in the generation of energy services (σ^{ela}). We further distinguish between scenarios in which households are confronted with demand rigidities and scenarios in which these do not play a role. To account for sensitivity of the model results with regard to these key parameters, we run the simulations for a set of different scenarios.

In our simulations, we will distinguish between three main sets of simulations. An overview of the scenarios is given in Table 1. The first scenario (*NO-HAB*) is a standard rebound scenario as it can be found in the standard literature on rebound. We increase $\gamma_{(el)}$ by 10% to see the impact of an increase of behavioural efficiency in absence of habits and demand rigidities. The second set of simulations will feature energy service consumption habits. In this scenario (*HAB-DR*), we distinguish between model runs with five different levels of demand persistence to account for variation in degree by which households demand is driven by habits. Furthermore, the scenario features the demand rigidity restriction that prevents households from buy new appliances in the short-run. In the third scenario (*HAB*), we will drop the demand rigidity restriction.

These sets of simulations are complemented with variations of the substitutability in the consumption of energy services, i.e. the elasticity of substitution between electricity and appliances. By varying the elasticity like in formal discussion of the stylised model in Section 2.1, we are able to quantify how this impacts the rebound effect. For our main scenarios, we assume that the energy service consumption of households is characterised by a CES function featuring an elasticity of substitution of 0.42. This value corresponds to the energy service substitution elasticity between value added and energy in inland transportation given in [Koesler and Schymura \(2012\)](#). Other values for this elasticity are chosen arbitrarily to check

Table 2: Energy Consumption Changes in the NO-HAB Scenario

Scenario: NO-HAB	σ^{ela}			
	0.00	0.42	1.00	1.20
Total energy service consumption	0.46%	0.50%	0.55%	0.57%
Energy service electricity use	−8.67%	−5.10%	0.00%	1.82%
Household energy use	−3.75%	−2.20%	0.00%	0.79%
Economy-wide energy use	−1.71%	−1.00%	0.00%	0.36%
Other final consumption	0.01%	0.01%	0.01%	0.01%

for sensitivity with regard to the importance of σ^s and the demand rigidity and the resulting change in input intensity as discussed in Section ???. We will show that the elasticity between electricity and appliances in the consumption of energy services is a very important parameter in the evaluation of rebound results. Assuming constant expenditure shares on final goods, the elasticity of substitution between energy services and other consumption is equal to one in all scenarios.

3.4 Simulation Results

In this section, we present the economy-wide implications of a costless and permanent behavioural efficiency shock of 10% in energy service consumption of households in Germany. We start with investigating the impact of the model shock without any habits or demand rigidities in the *NO-HAB* scenario and then compare the results to the benchmark situation without any behavioural efficiency shock. The results are displayed in Table 2

3.4.1 Rebound in the Absence of Habits and Demand Rigidities

The resulting changes in energy and other final consumption that are due to the behavioural efficiency improvement in a setting without habits and demand rigidities are given in Table 2. Naturally, the effects of the efficiency shock originate from the generation of energy services by households. As electricity becomes more effective, input cost are reduced and the cost for one unit of energy services decrease. Consequently, the demand of households for energy services and thus also its production increases between 0.46% and 0.57% depending on the elasticity of substitution σ^{ela} . Resulting from the increased consumption of energy services, the demand for appliances (*MACH* and *ELEQ*) increases. In the case of an elasticity of substitution of $\sigma^{ela} = 0.42$, demand for appliances increases by 1.48% while the demand for electricity decreases by 5.10% in *natural* units. The changes in electricity demand in household consumption of energy services can thus be attributed

to the the first and second term on the right hand side of Equation (??) from the stylised example presented in the previous section, i.e. changes in input intensity and current demand.

We further see that the higher the elasticity of substitution is between electricity and appliances in the consumption of energy services, the lower is the actual saved electricity. For the *NO-HAB* scenarios with a high elasticity of substitution $\sigma^{ela} \geq 1$, we see that electricity use remains constant for the Cobb-Douglas production case of $\sigma^{ela} = 1$ which is due to the fact that input shares remain the same. In the case of an elasticity of substitution of 1.20 the energy service electricity use is even higher than before the behavioural efficiency change as households substitute away from appliances and use more of the cheaper energy.

Over all elasticity cases we see that other final consumption is only increasing by a very small amount of 0.01%. As households need to spend less on electricity, they can consume more. This includes energy as well as other goods and services. All this should in general have a positive effect on all sectoral outputs. The additional demand by households on energy service related sectors puts upward pressure on prices and increases input costs of all sectors. However, in the *NO-HAB* scenario, these changes are marginal.

In terms of demand for energy (all measured in *natural* units), we observe an economy-wide decrease of energy use in Germany of -1.78% when there is no substitution, a 1.00% decrease with $\sigma^{ela} = 0.42$, no change in the Cobb-Douglas case $\sigma^{ela} = 1.00$ and an increase of 0.36% in with $\sigma^{ela} = 1.20$. German household demand for energy reduces by 3.75% ($\sigma^{ela} = 0.00$) and 2.20% ($\sigma^{ela} = 0.42$) and increases by 0.79% in the case of $\sigma^{ela} = 1.20$. These results illustrate that energy savings are eroded by an important share by substitution effects.

The changes in energy use leads us to the main point of interest, the rebound effect. Figure 3 displays our results regarding the rebound effect in absence of habits and demand rigidities in household energy service consumption following our rebound definition in Equation (6).

We see that the rebound take different values depending on the chosen elasticity in the simulation. As we could already see in Table 2, the greater the elasticity of substitution between electricity and appliances in the consumption of energy services, the less energy savings translate into actual energy savings from the efficiency shock. In the case of an elasticity $\sigma^{ela} \geq 1$ we even see a situation in which the rebound completely negates the energy savings and households actually use

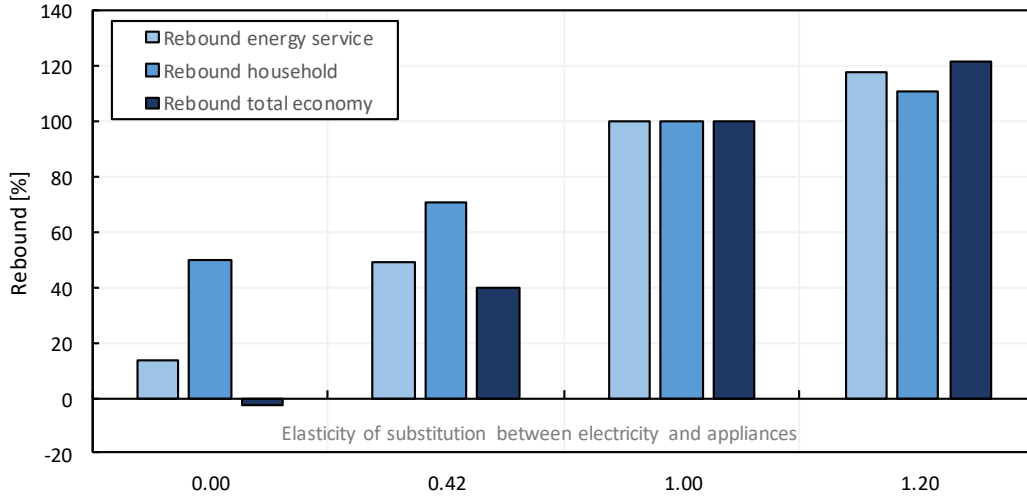


Figure 3: Rebound in the Absence of Habits and Demand Rigidities

more energy than before the efficiency shock ($\sigma^{ela} = 1.20$).

If households are less flexible in their substitution between electricity and appliances ($\sigma^{ela} = 0.42$), 49% of the behavioural energy efficiency improvement in the consumption of energy services is lost due to the rebound. Due to the absence of substitution effects when households are inflexible in their consumption ($\sigma^{ela} = 0$), the loss is much lower and amounts only to 13%. The rebound on the level of total household energy consumption is 71% and 50%, respectively. The increase of the rebound effect when changing from the energy service perspective to a more comprehensive household perspective can be explained by the additional energy consumption of households. This additional consumption is due to lower costs in the consumption of energy services when these services become more energy efficient.

Broadening the scope of the rebound to an economy-wide perspective, results in a rebound of 39% for $\sigma^{ela} = 0.42$. The energy savings from the behavioural energy efficiency improvement are amplified by the reduction of sectoral output in particular in energy intensive sectors such as *SecE* and *MINI*. As a consequence rebound is reduced. Our findings are in line with [Lecca et al. \(2014\)](#) who postulate that the rebound effect on the economy level should be smaller than the rebound on the household level if total energy consumption decreases. As a matter of fact, the total German energy demand decreases so greatly that we can report a negative rebound effect of -3% for the *NO-HAB* scenario with $\sigma^{ela} = 0.00$. Thus, in this

Table 3: Energy Consumption Changes in the HAB Scenarios

Scenario: HAB	Strength of habit persistence (θ^s)				
	0.10	0.20	0.30	0.40	0.50
Total energy service consumption	0.69%	0.85%	0.96%	1.03%	1.04%
Energy service electricity use	-4.94%	-4.82%	-4.73%	-4.70%	-4.72%
Household energy use	-2.01%	-1.82%	-1.65%	-1.48%	-1.32%
Economy-wide energy use	-0.96%	-0.92%	-0.90%	-0.87%	-0.86%
Other final consumption	0.23%	0.47%	0.72%	0.99%	1.27%

special case, the usually counterproductive rebound channels eventually generate an additional benefit. In the simulations with $\sigma^{ela} \geq 1$, all rebound values are above 100% and the rebound completely negates the efficiency improvements. In the case of $\sigma^{ela} = 1.20$ we see that the economy-wide rebound is larger than the rebound on household level, leading to a situation in which energy consumption is higher than in the benchmark without the increase in behavioural efficiency.

3.4.2 Rebound in the Presence of Habits and Demand Rigidities

As previously illustrated formally, consumption habits can have an initial negative effect on rebound triggered from an energy efficiency improvement. Unless otherwise specified, the elasticity of substitution will be fixed to $\sigma^{ela} = 0.42$ in the following to focus on the impact of habits and demand rigidities on the rebound effects. Table 3 provides an overview of the impacts of a 10% behavioural energy efficiency increase in the consumption of energy services in the presence of consumer habits on energy and other consumption compared to the benchmark situation without the behavioural efficiency shock.

If households are ready to substitute but are bound by habits (*HAB* scenarios), household electricity demand for the consumption of energy services is higher than in the absence of habits (*NO-HAB*: -5.10%) as energy service consumption is increasing compared to the *NO-HAB* scenario. The greater the strength of the habit, the higher is the additional energy service consumption. This also holds true for the total energy consumption of households and the economy-wide energy use. However, as we increase the households' habit persistence in our simulations and thereby increase the demand for energy services, energy prices also rise. This limits the consumption of energy services and leads to an increase in other consumption, which becomes relatively cheaper.

Analysing the rebound, we see that the expanded energy service consumption re-

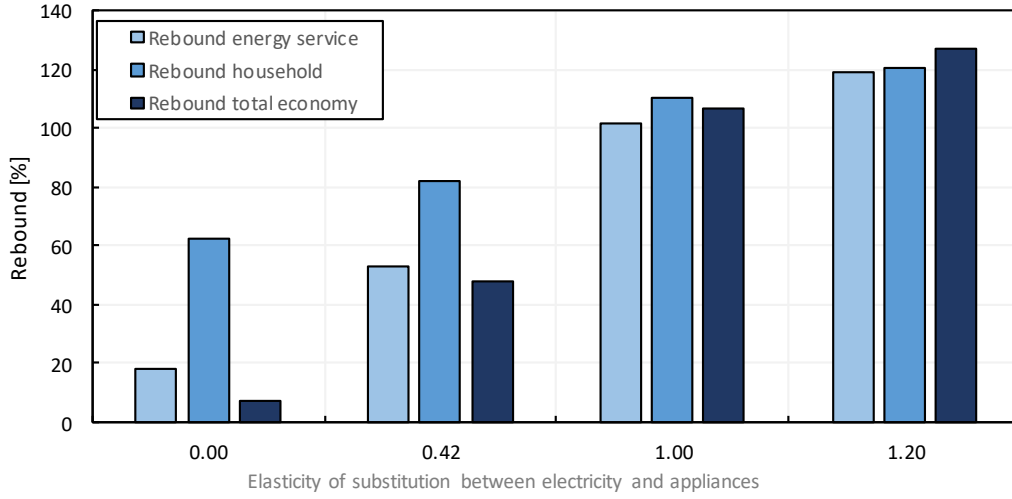


Figure 4: Rebound in the Presence of Habits

sults in an initial reduction of the rebound effect for the *HAB* scenario as predicted in our theoretical model. Results for the *HAB* scenario with $\theta^s = 0.5$ and different elasticities of substitution are displayed in Figure 4.

In the case of an elasticity of substitution of $\sigma^{ela} = 0.42$ and a habit of $\theta^s = 0.5$, energy service rebound is increasing by 3.78 percentage points to about 53%, household energy rebound by 11.72 percentage points to 82% and the total economy rebound by 8.58 percentage points to 48%. Compared to a situation without a habit, rebound effects are larger in all habit scenarios. As demonstrated in the theoretical model, the CGE analysis confirms the importance of the elasticity of substitution in energy service consumption. The difference between the energy service rebound in the case of an elasticity of substitution of 0.00 and 0.42 amounts to 41 percentage points and is due to the fact that without the ability to substitute appliances and electricity, the consumption of energy services remains limited. The results for the energy service rebounds in case of a elasticity of substitution above 1 are in a similar magnitude as in the *NO-HAB* scenario, while the rebound in final demand (rebound household) is 82% which is 11.72 percentage points more than in the scenario without habit. The total economy rebound is 48%, which is 8.58 percentage points above the rebound in the *NO-HAB* scenario.

In the next scenario (*HAB-DR*), we look at a situation in which additional demand rigidities restrict the purchases of new electric appliances. This is a reasonable assumption as households can have high opportunity costs of switching and can

Table 4: Energy Consumption Changes in the HAB-DR Scenarios

Scenario: HAB-DR	Strength of habit persistence (θ^s)				
	0.10	0.20	0.30	0.40	0.50
Total energy service consumption	0.23%	0.24%	0.24%	0.25%	0.25%
Energy service electricity use	-5.11%	-5.01%	-4.91%	-4.82%	-4.74%
Household energy use	-1.99%	-1.79%	-1.58%	-1.38%	-1.18%
Economy-wide energy use	-0.98%	-0.94%	-0.91%	-0.87%	-0.84%
Other final consumption	0.39%	0.68%	0.96%	1.26%	1.55%

therefore be deterred from switching. The impact on energy demand is displayed in Table 4.

We see that restricting the purchases of new appliances has a limiting effect on the consumption of energy services and thus also on the rebound effect. The additional energy service consumption we saw in the *HAB* scenarios is reduced to between 0.23% and 0.25% in the *HAB-DR* scenarios. Consequently, the demand rigidity also limits the consumption of electricity, which is slightly lower in the *HAB-DR* scenario. In the presence of the demand rigidity, the behavioural efficiency improvement leads to a shift of the rebound to other channels.

Compared to other scenarios, other final consumption like consumption of food or services from the tertiary sector is higher in the case of existing demand rigidities in energy service consumption. Parts of this increase can be attributed to the fact that a reduction in prices for energy services generates additional household demand through income effects. If we compare the *HAB* scenario with a habit persistence of $\theta^s = 0.5$ with the *HAB-DR* scenario with the same habit persistence, we find that, not surprisingly, output in the 'Machinery' and (*MACH*) and 'Electrical and Optical Equipment' (*ELEQ*) sectors are 1.26%, respectively 0.86% lower in the presence of demand rigidities. This is due to the reduced consumption of energy services caused by the demand rigidity. Other sectors like 'tertiary sector' (*TERT*), 'transport activities' (*TRAN*) and 'transport equipment' (*TREQ*) experience an increase in output, with increases of 0.14%, 0.07% and 0.05% respectively. If we include imports, the total other consumption level households is increasing by 0.27% compared to the *HAB* scenario.

Furthermore, due to the shifts in consumption caused by the demand rigidity, economy-wide energy usage increases compared to the *HAB* scenario as energy prices are lower. These results show the importance of considering all possible rebound channels. Our findings depict that the restricting nature of demand

Table 5: Rebound Scenario Comparison

Scenario Comparison	Scenario		
	NO-HAB	HAB*	HAB-DR*
Rebound energy service (household electricity use)	49%	53%	53%
Rebound household (final demand energy use)	71%	82%	84%
Rebound total economy (total energy use)	39%	48%	49%

*Strength of habit persistence $\theta^s = 0.5$

Note: $\sigma^{ela} = 0.42$ in all scenarios

rigidities in energy service consumption is an important aspect that needs to be considered in rebound analyses in the household sector.¹

We conclude our analysis with a comparison of the rebound results of the three analysed scenarios. Table 5 displays the results for the comparison of the *NO-HAB* scenario with the *HAB* and *HAB-DR* scenario that feature a habit persistence of $\theta^s = 0.5$. Compared to the benchmark without behavioural efficiency improvement, electricity consumption reduces by -4.72% in the *HAB* scenario and by -4.74% in the *HAB-DR* scenario as illustrated in the previous tables. The calculated rebound effect in energy service is therefore almost the same size (53%) in both cases. However, as people spend less on new appliances and thereby have a lower energy service consumption than in the *HAB* scenario, the other rebound effects are higher in the *HAB-DR* scenario.

We can further observe that in the *NO-HAB* scenario without habits and demand rigidities, all rebounds are smaller than in the two scenarios with the habit persistence. While the difference in the energy service rebound amounts to 4 percentage points, the difference in the total economy rebound is 9 percentage points and the difference in household rebound is even 11. The comparison illustrates once again that when analysing the rebound effect in the household sector, it is crucial to consider consumer habits and demand rigidities. Our results further show that in such an analysis of the rebound effect it is important to take into account the economy-wide perspective, which can best be achieved with a CGE model. If these factors are not taken into account, the calculated rebound effects can be significantly too small, as we can see in the comparison with the *NO-HAB* Scenario.

¹Since the rebound results with different elasticities in energy service consumption of the demand rigidity simulations are of a similar order of magnitude as the rebound results from the habit case without demand rigidities (see Figure A.1 in Appendix A.2), we will not go into this again at here.

4 Conclusion

In this paper, we extend the analysis of household’s energy service consumption by investigating the rebound effects of behavioural efficiency improvements in households in the presence of consumption habits and demand rigidities. We set up three main scenarios and investigate the impact of a 10% behavioural energy efficiency improvement in the consumption of electricity using energy services by German households in a CGE model that features a comprehensive representation of energy services consumption.

We demonstrate that rebound effects have the potential to significantly reduce the expected energy savings of behavioural energy efficiency improvements. The rebound in energy service consumption, as well as total energy rebound of the household and the economy-wide rebound exhibit values that should not be neglected. In that sense, our results are in line with [Lemoine \(2020\)](#) and others who show that rebound is not a negligible side effect.

By implementing energy service consumption habits and demand rigidities in our analysis, we are the first who shed light on the importance of consumer-specific particularities that influence energy service consumption. Taking into account that households electricity consumption features habits shows that the resulting rebound erodes even larger parts of the efficiency increases. In our setting, rebound in energy service consumption amounts to up to 53% or more if we allow for extreme values of the elasticity of substitution, which means more than half of the behavioural efficiency improvement is eroded by the rebound. Through the implementation of demand rigidities in our analysis we were able to show that the increase in energy service consumption can be limited. We further demonstrate the relevance of the different rebound channels, as substituting to other energy intensive goods is still possible, even if energy service consumption is restricted by demand rigidities.

In the context of behavioural or technical energy efficiency improvements in households, taking into account rebound effects is therefore very important. Our analysis provides important policy implications, as changes in energy consumption behaviour of households that lead to a higher energy-efficiency are believed to be crucial to reduce global energy consumption and achieve sustainability. Policy makers should therefore be fully aware of the associated rebound potential. This is especially the case when households have energy service consumption habits that amplify the rebound effects. A policy that aims at reducing energy consumption of households should therefore always take consumption habits into account, as otherwise the rebound effect might be underestimated.

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A Appendix

A.1 Tables

Table A.1: Regional aggregation

Short	Region	Associated WIOD Regions
DEU	Germany	DEU
EU	EU26 (without Germany)	AUT, BEL, BGR, CYP, CZE, DNK, ESP, EST, FIN, FRA, GBR, GRC, HUN, IRL, ITA, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROM, SVK, SVN, SWE
ROW	Rest of the World	AUS, BRA, CAN, CHN, IDN, IND, JPN, KOR, MEX, ROW, RUS, TUR, TWN, USA

Table A.2: Sectoral aggregation

Short	Sectors	Associated WIOD Sectors
FOOD	Food, Beverages, Tobacco	15t16
COPN	Coke, Petroleum, Nuclear Fuel	23
CHEM	Chemicals and Chemical Products	24
META	Basic Metals and Fabricated Metal	27t28
MACH	Machinery, n.e.c.	29
ELEQ	Electrical and Optical Equipment	30t33
TREQ	Transport Equipment	34t35
TRAN	Transport Activities	60, 61, 62, 63
AGRI	Agriculture, Hunting, Forestry and Fishing	AtB
MINI	Mining and Quarrying	C
ELGW	Electricity, Gas and Water Supply	E
SECO	Secondary Sector	17t18, 19, 20, 21t22, 25, 26, 36t37, F
TERT	Tertiary Sector	50, 51, 52, H, 64, J, 70, 71t74, L, M, N, O

A.2 Figures

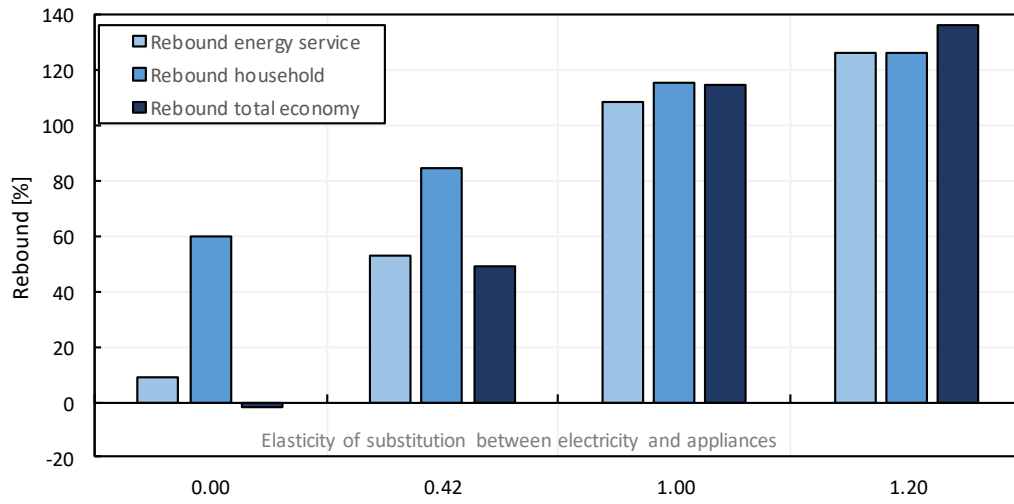


Figure A.1: Rebound in the Presence of Habits and Demand Rigidities