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* (Khazzoom, 1980). 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 should not be neglected (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 macroeconomic impact of energy efficiency improvements has so far primarily been concentrated on the production side of the economy (see e.g. Lemoine, 2020, Koesler et al., 2016, Turner and Hanley, 2011).

There is only a small number of studies on the effects of an efficiency improvement of households on the economy. 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 to measuring rebound at both the full economy and household levels. In doing so, they study the impact of improving efficiency in the use of energy on the consumption of energy services in British households. 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. We then apply the mechanism in a more general framework and examine the rebound effect based on a CGE model. Finally, we summarise our results and conclude.

2 Theoretical Considerations

Before we turn to a broader setting to analyse 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 provide a description of the rebound effects that we will 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. Households rarely actually consume commodities, such as light bulbs and electricity or a heater and fuel. Households combine these intermediate goods to produce services 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. We follow the theoretical model in Koesler (2013) and include a habit in the household problem. The habit is modelled as a energy service consumption habit. To achieve that we use a Stone-Geary utility function. This type of function contains an expression that can be interpreted as a 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:

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

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 is given by θ_s, with $\theta_s < 1$. Note that for simplicity we follow Koesler (2013) and limit the habituation to one period, as 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. Households have, by assumption, a fixed income M which is not affected by the change in efficiency.

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

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

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:

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

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:

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

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:

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

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 causes the amount of energy e used to consume the energy service to change due to 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 occurs when gains in efficiency in the consumption of energy services lead to a decline in the actual 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 $\sigma = 1$, (Cobb-Douglas consumption function) energy intensity remains constant.

The indirect rebound effect refers to a situation in which a reduction in the actual price of an energy service as a result of more efficient consumption of the energy service also relaxes the consumer's budget constraint. (Sorrell and Dimitropoulos, 2008). This income effect allows households to demand more from other products and services. 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 lead to an increase in energy consumption in other related sectors, negating the benefits of the energy efficiency change. It describes the rebound that occurs at the macro-wide level, in an economic environment where all prices and quantities are endogenous and the efficiency improvement can lead to secondary price and quantity adjustments that take place in connected sectors. To take all these price and quantity adjustments into account, it will be is 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. In this case all other things remain constant and a 10% efficiency increase of an input will result in a 10% decrease of the input usage. We follow Lecca et al. (2014) and Koesler (2013) and measure rebound using the ration between the change in energy use 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

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

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. ΔE_s is the change in energy use in this scope. 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 consider the rebound effect in a full-scale CGE model. The CGE model incorporate all the important features of the stylised example discussed in 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 Pothen, 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.

A KLEM production function structure is used, in which 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.

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,

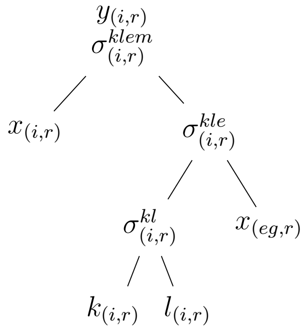

Figure 1: KLEM Production Function

energy service consumption in region r is described by:

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

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.

The utility function distinguishes 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 to be able to investigate the effects of a change in the efficiency of energy service consumption. 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:

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

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 households have consumption habits then they only adjust part of their consumption bundle to the current situation. The other part of their consumption 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:

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

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 in Section 2.1, 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 by the respective substitution elasticities σ^{sz} and σ^{egi}. The structure of the utility function is shown in Figure 2.

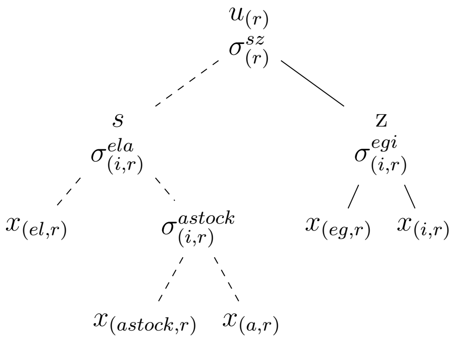

Figure 2: Household Consumption Structure

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 counter-productive 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 CO_2 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. Therefore, we abstract from interregional effects in our analysis and focus on Germany. The aggregation schemes are 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 energy service consumption data was disaggregated to allow for a explicit modelling of 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 in 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).

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 with the shares of the fictive inputs varying depending on the type of accompanied energy good (Koesler and Pothen, 2013).

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.

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}) are further important parameters. We additionally distinguish between scenarios in which households are confronted with demand rigidities and scenarios in

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.

which these do not play a role. We run the simulations for a number of different scenarios to test the sensitivity of the results with respect to these key parameters.

In our simulations, we will distinguish between three main sets of simulations. The scenarios are shown 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. 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 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 2.2. 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.

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%

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. As the effectiveness of electricity increases, the input cost and the cost of a unit of energy service decreases, which increases the demand of households for energy services. As a result, their production also 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. Thus, the changes in electricity demand in the consumption of energy services by households can be attributed to the input intensity and demand in the current period. (see equation (5).

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

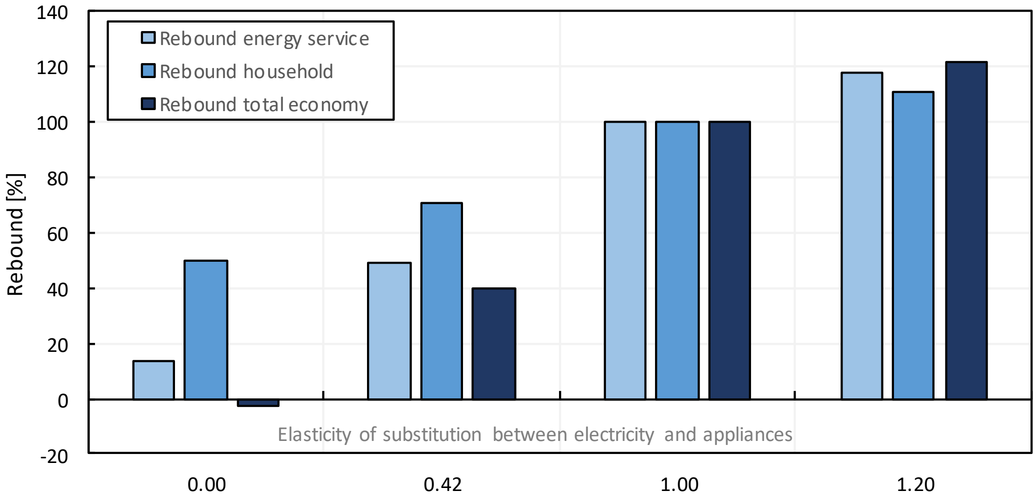

Figure 3: Rebound in the Absence of Habits and Demand Rigidities

away from appliances and use more of the cheaper energy. This includes energy as well as other goods and services, which should generally lead to an increase in all sectoral outputs. Moreover, additional household demand for energy services additionally increases prices in sectors related to energy services and input costs for all sectors.

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. However, in the *NO-HAB* scenario, these changes are marginal.

For the demand for energy, which is all measured in *natural* units, we observe an total 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 offset to a large extent by substitution effects.

The effects on energy use take us to the primary topic of our analysis: 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).

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%

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 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 more limited and totals only 13%. The rebound on the level of total household energy consumption is 71% and 50%, respectively. The increase in the rebound effect when switching the focus from energy services to a broader household perspective can be explained by the additional household energy consumption. This additional consumption is due to lower costs in the consumption of energy services when these services become more energy efficient.

Extending the rebound to an all-economy view, results in a rebound of 39% for $\sigma^{ela} = 0.42$. Energy savings from behavioural energy efficiency improvement are enhanced by reductions in sectoral output, especially in energy-intensive sectors such as $SecE$ and $MINI$, which reduces the rebound effect. Total German energy demand falls so sharply that we can show a negative rebound effect of −3% for the *NO-HAB* scenario with $\sigma^{ela} = 0.00$. 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

Consumption habits may have an negative effect on rebound as formally illustrated previously. 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 willing to make substitutions but are tied to 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 results in a smaller rebound 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.

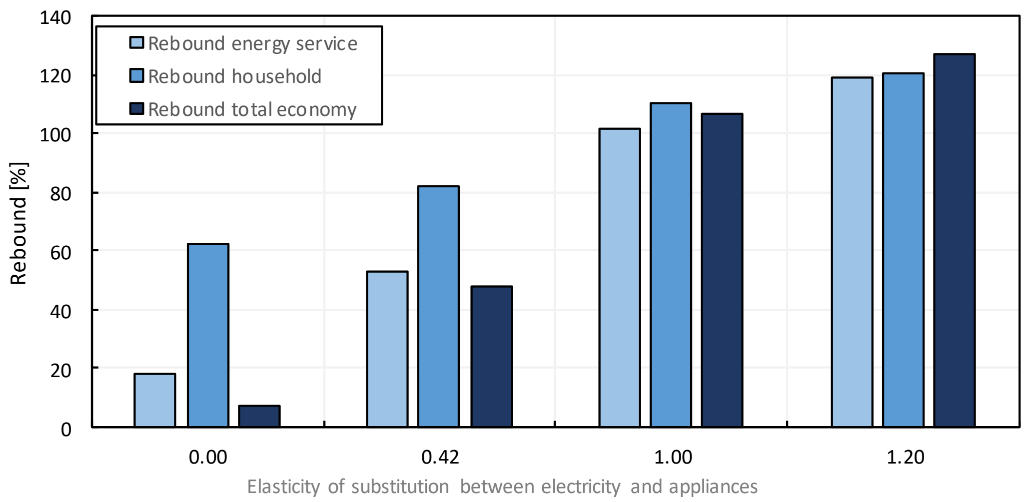

Figure 4: Rebound in the Presence of Habits

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%

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 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. 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 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

[1]Since 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.

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

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.

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 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 made fully aware of the potential setback involved. 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

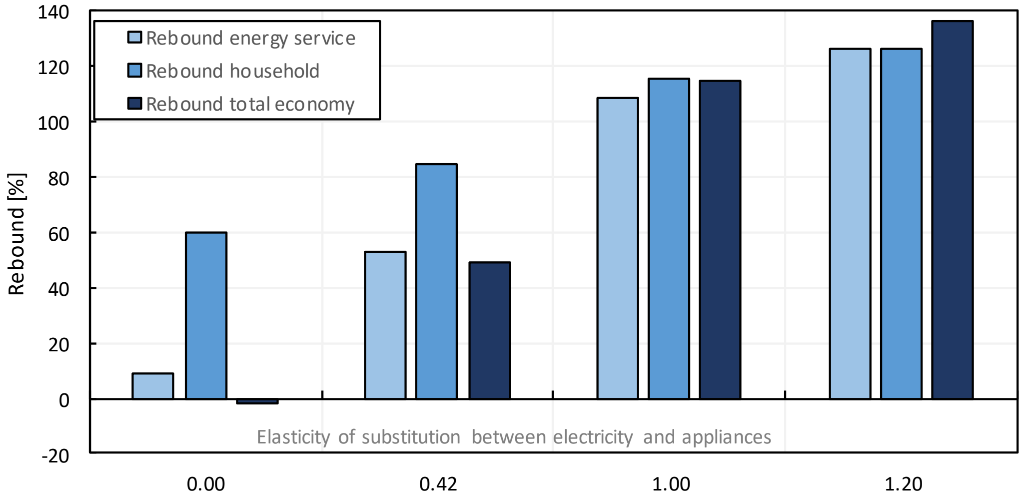

Figure A.1: Rebound in the Presence of Habits and Demand Rigidities