Impacts of consumers' electricity price misperceptions*

Martin Baikowski†

University of Münster

November 11, 2018

Abstract

Empirical findings indicate that a large share of households misperceives electricity prices and is not able to make deliberate choices in energy service consumption, which leads to biased consumption decisions and thus to inefficient energy use. To investigate the impact of misperceived electricity prices on the derived demand for electricity, the economy and domestic CO_2 emissions, we make use of a computable general equilibrium (CGE) model. The model allows us to take the narrow interweaving of production and consumption sectors into account to investigate the repercussions on supply and demand in Germany and Europe. Providing information on electricity prices or the most efficient utilisation can stimulate reductions in electricity consumption if households are aware of possible trade-offs. However, if consumers perceive the electricity price to be much higher than it actually is, providing information on the true electricity price might turn out to be counter-productive in terms of electricity consumption and domestic CO_2 emissions.

JEL Classification

D58, Q41, Q43

Keywords

Residential energy consumption; energy efficiency; behavioural inefficiency; electricity price misperception; consumer inattention

*We acknowledge financial support from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723791 - project PENNY "Psychological, social and financial barriers to energy efficiency".

†University of Münster, Am Stadtgraben 9, D-48143 Münster, Germany; Email: martin.baikowski@uni-muenster.de

1 Introduction

Increasing energy efficiency has been identified to be one of the central objectives in the transition processes towards low-carbon economies globally. The European Union aims to improve energy efficiency by at least 27% for the year 2030, compared to projections of future energy consumption.[1] As residential consumption accounts for about 25% of the total final energy consumption in the EU-28 region in 2016 (Eurostat, 2017), making up a non-negligible share of about 5% of total household consumption expenditure, consumers are expected to take a more active and central role in the energy markets of the future. The EU's drive towards a more energy efficient future hence also targets the demand side of the energy markets. The idea of policies targeting the demand side is to encourage households to invest in more energy efficient technologies and to adjust their consumption plans to exploit potential energy savings. Substantial reductions in households' energy demand are crucial for achieving ambitious greenhouse gas emission reduction goals.

Despite the apparent significance of residential energy demand, only few numerical models exist that examine the wider impacts of changes in the behavioural factors that underlie adjustments in household energy demand. Typical demand models assume that consumers are perfectly informed optimising agents, i.e. agents that possess a combination of perfect information about product attributes and unbounded computational capacity to understand how each attribute maps into utility (Allcott, 2013). However, experiments in both the psychology literature and the economics literature raise questions about these assumptions (Allcott and Taubinsky, 2015, DellaVigna, 2009).

As has long been observed in experiments, consumers do not adopt some energy-efficient technologies despite large financial savings, a phenomenon commonly referred to as the *energy efficiency gap* (Gerarden et al., 2017, Jaffe and Stavins, 1994). While part of this literature primarily looks at the energy efficiency potential that might be reached through investments, a closely linked strand of literature analyses behavioural explanations for inefficiencies in the consumption of energy services.[2] Households might for example be inattentive towards energy conservation or possess only imperfect knowledge about how goods are most efficiently used in the consumption of energy services.

Households further seem to have limited knowledge about energy costs, although they represent a non-negligible part of their total expenditure. Focusing on electricity, Brounen et al. (2013) illustrates this with a survey of 1,721 Dutch households, in which only around 47% of the respondents are aware of their monthly electricity expenses. More recent findings by Blasch et al. (2017) indicate that Swiss households misperceive the costs of electricity consumption and therefore misvalue energy costs relative to their private optima. They further state that this inefficiency is indicative of structural problems faced by households and systematic behavioural shortcomings in residential electricity consumption.

A more recent study by Boogen et al. (2018) supports these findings and shows that electricity price misperceptions[3] vary across countries. In the representative survey they conducted in four European countries, households were asked to guess the average electricity price for household consumers in their respective country. The results expose average electricity price misperceptions between −16.67% and +18.75% in the surveyed countries.[4] Reasons for these biased beliefs might be inattention (Gerarden et al., 2017) or a lack of energy literacy, which

[1]More recently, the Commission reached a political agreement which includes a binding energy efficiency target for the EU for 2030 of 32.5%, with a clause for an upwards revision by 2023.

[2]see e.g. Allcott and Rogers (2014), Attari et al. (2010), Harding and Hsiaw (2014), Taubinsky (2013).

[3]We define the electricity price misperception to be the relative deviation of the median answer from the actual average electricity price including taxes in the respective country.

[4]Table 7 in Appendix A.1 presents the survey results and the median misperception for Switzerland, the Netherlands, Italy, and Germany.

can be defined as an individual's ability to make informed and deliberate choices in the domain of household energy consumption (Blasch et al., 2017).

Allcott (2010) stresses that whether choices are driven by true preferences or a misperception of product attributes and costs has important economic meaning and consequences for policy implementation. In the case of a misperception, consumers are making ex-ante decisions which will reduce their (ex-post) realised welfare. He further points out that these biased decisions can, in principle, be corrected through information disclosure. The consumption of energy services is one example of such a decision. A misperception of the energy prices associated with the energy service influences the consumption decision and thereby leads to a consumption and production structure that would look different under perfect information. As emphasised by Hunt and Ryan (2015), energy is typically not desired for its own sake, but for the energy service it provides (e.g. lighting or heating) and energy demand models, both theoretical and empirical, often fail to take account of this feature. Considering that, also the demand for appliances that use energy are affected by this misperception, as energy efficiency will not be perceived as an important characteristic of these appliances. Due to the narrow interweaving of the involved production sectors, the misperception also has an indirect impact on other production sectors of the domestic economy and repercussions on supply and demand of other countries. Households' preferences that exhibit a trade-off in consumption have great repercussions on the impact of behavioural shortcomings. Sorrell and Dimitropoulos (2008) underline that the consumption of energy services involves several interrelated trade-offs. One example is the trade-off between consuming energy services and other consumption goods as described above. A possible overuse of energy in the residential sector for example prevents households from spending more on other consumption goods and appliances with a higher energy efficiency. Eliminating misperceptions in the residential sector therefore could turn out to increase the production in other sectors and thereby also CO_2 emissions in these sectors. Another very important modelling aspect that needs to be taken into account is the functional form that describes the energy service consumption and links energy consumption to the choice for the appliances that use it, such as heaters or lightbulbs. Hence, there are also substitution possibilities among the energy services that need to be taken into account in the modelling of energy services. This trade-off has important implications for future consumption since the expenditure on such appliances can be seen as an investment in capital goods by the consumer. Households can for example choose between a very energy efficient fridge or a less efficient one to obtain the same service (e.g. cooling beverages). Assuming that all other characteristics (i.e. size, colour, position, etc.) stay the same, the more expensive fridge is (usually) more energy efficient, i.e. needs less electricity to produce the same service.

Only a few CGE models exist that are focused on the demand side and take into account the explicit modelling of energy services. Lecca et al. (2014) utilise a CGE model to investigate the impact of an efficiency improvement in the use of energy in UK household consumption. They distiguish between the consumption of energy and non-energy commodities and compute total energy rebound values. Figus et al. (2017) are interested in the wider implications of vehicle-augmenting efficiency improvements. Using a partial equilibrium approach, they model private transport consumption as a household's self-produced commodity formed by a vehicle and fuel use. They extend their analysis with computable general equilibrium 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 central aim of this paper is to analyse the impact of misperceived energy prices and behavioural inefficiencies in energy service consumption on the consumer demand, the associated impact on production sectors in Germany and Europe and CO_2 emissions. We make use of a CGE model to take into account endogenous price changes and the linkages between regions and markets. This allows us to analyse regional and global demand and supply effects. We also take up the critique by Hunt and Ryan (2015) and add to the discussion by introducing a more elaborate energy services consumption structure that incorporates electricity as a derived demand in the consumption of energy services. As a result, we extend the energy service consumption literature that is so far mainly focused on productivity improvements in the consumption of private transport services and does not cover behavioural inefficiencies.

The remainder of this paper is structured as follows. In the next section, we formally describe the energy service consumption and the consumer's misperception of electricity prices. We then describe the numerical model, data and calibration before we present our simulation strategy and the results. The last section concludes.

2 The Model

In this section, we give a formal illustration of energy service consumption and the consumer's misperception of electricity prices. After that, we describe the enhanced version of the CGE model that explicitly takes into account this consumer behaviour and present our simulation strategy.

2.1 Analytical Framework

Since energy is typically not desired for its own sake, but for the service it provides, we distinguish between the energy good, and the appliances that use energy as an input. Energy is used in conjunction with an appliance which can be seen as a certain type of capital good (e.g. electric appliances, boilers, cars) that incorporates a certain (energy) efficiency in providing the required services.

The energy service good is a composite of the energy good e and an appliance (capital) good x, e.g. the energy service *lighting* is a composite good consisting of expenditure on the energy good *electricity* and expenditure on a *light bulb*. This composition can be determined by calibrating a constant elasticity of substitution (CES) function f with constant returns to scale such that $s = f(x, e)$. In our model, the representative consumer chooses s units of the energy service good and z units of a numeraire good such that her utility from consuming these goods is maximised given her budget constraint,

$$\begin{aligned} \max_{x,e,z} \quad & u(s, z) \\ \text{s.t.} \quad & s = f(x, e) \\ & \widetilde{p_e} e + p_x x + z = M, \end{aligned} \tag{1}$$

where M denotes the consumer's income, $\widetilde{p_e}$ the perceived energy price and p_x the price of the appliance.

Notice that we treat household purchases of appliances as a flow of current consumption. In reality, of course, electric appliances are capital goods that depreciate over time and provide a service flow over their respective lifetime. We abstract from this specification in this stylised model. We take into account that the consumer might misperceive her expenses for energy services and formalise this as a systematic bias by assuming that the misperception depends on the perceived energy price $\widetilde{p_e}$. The systematic bias is therefore a consistent underestimation (or overestimation) of the energy price if $\widetilde{p_e} \neq p_e$, where p_e is the true energy price. A misperception of the price of a good results in a biased demand, i.e. a demand that would be higher or lower (depending on the sign or direction of misperception) when compared to the demand under market prices.

The budget of the household is made up of the revenues from the rental of $\bar{K}$ units of primary factor capital and $\bar{L}$ units of labour, which are assumed to be fully utilised in equilibrium. It further includes any transfer payment that is associated with the difference between the true and the perceived energy costs.

$$M = p_l \bar{L} + p_k \bar{K} + \Psi \tag{2}$$

At the end of the year, the household receives its energy bill and pays the true energy price. As the consumer is assumed to be very myopic, she will not update her price beliefs but take the new budget as given. We model this as a lump-sum payment (Ψ) to the consumer and assume that this payment increases respectively reduces the budget depending on the direction of misperception. We can think of this lump-sum payment as, for example, the end of year payment each consumer receives to balance out budgeted payments to the energy company and actual costs of electricity.

The household is assumed to be not able to associate the payment with its energy service consumption and views these transfers to be independent of any decision she makes. By incorporating the misperception in this way, we are able to demonstrate the distortionary impact of the price misperception. Due to the misperception of the electricity price, the consumers demand for energy services is biased.

We can think of this household's optimisation problem as a two-stage optimisation problem that consists of a lower and an upper stage. In its lower stage, the consumer minimises the expenditure on energy and associated appliances, to obtain the necessary units of the energy service good. In the upper stage of the optimisation problem, the household then chooses the optimal amounts of energy services s and market goods z to maximise utility.

Assuming homotheticity of the utility function, let $\mathrm{ex}^s(p_x, \widetilde{p_e}, s)$ denote the minimum expenditure for consuming s units of the energy service given the appliance's input price p_x and the perceived energy price $\widetilde{p_e}$,

$$\begin{aligned} \mathrm{ex}^s(p_x, \widetilde{p_e}, s) = \quad & \min_{x,e} \quad p_x x + \widetilde{p_e} e \\ & \text{s.t.} \quad\;\; s = f(x, e)\,. \end{aligned} \tag{3}$$

Then the price of the energy service s can be described by $\widetilde{p_s}$,

$$\widetilde{p_s}(p_x, \widetilde{p_e}, s) = \frac{\partial \mathrm{ex}^s(p_x, \widetilde{p_e}, s)}{\partial s}. \tag{4}$$

Typically, the price of energy services p_s is not observable (Hunt and Ryan, 2015), but incorporation into the CGE model allows us to quantify the price for energy service to equal the marginal cost of the energy service consumption, within the nested CES structure. The solution to the utility maximisation problem is described by the demand function for the energy service good $\widetilde{s}$,

$$\widetilde{s} = d(\widetilde{p_s}, M). \tag{5}$$

The demand for energy services $\widetilde{s}$ therefore depends on the energy service (shadow) price, $\widetilde{p_s}$ and disposable income, M. Due to the misperception of the electricity price, the consumers demand for energy services is biased.

2.2 Numerical Model

To account for the aforementioned trade-offs and analyse the impact of the electricity price misperception in the consumption of energy services, we incorporate the main elements of the analytical framework developed in Section 2.1 in a computable general equilibrium model. As we are interested in the spillover effects impacts on production and consumption in Germany and the EU, an extension of a multi-sector, multi-region CGE model is necessary. Using the

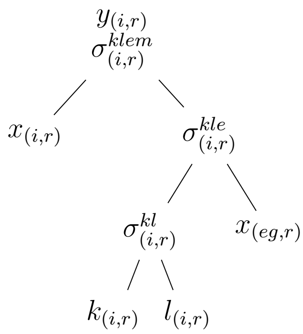


Figure 1: CGE Model production structure

CGE model, we are able to account for detailed production and consumption changes in the economy as it includes the interdependencies of factor and goods markets, and features several regions and its trade linkages. In our simulation, we focus on electricity, as it constitutes an indispensable energy good, but is non-transparent in its consumption at the same time. Other energy-intensive services, such as heating or private transportation, can be similarly seen as composite goods as in our model. However, to enhance tractability and to concentrate on the effect of electricity price misperception, we isolate energy services that use electricity in combination with electric appliances.

2.2.1 Model Description

We build on the WIOD CGE model[5], which is a multi-region, multi-sector computable general equilibrium model, since it partitions the world into several regions represented by a microeconomic utility maximising consumer household, where the multiple production sectors are represented in each region with a microeconomic profit maximising production household. The underlying production technology is modelled using a nested constant elasticity of substitution production function exhibiting constant returns to scale. This function consists of three nests to specify the substitution possibilities between capital, labour and intermediate goods.
Output can be produced from $x_{(eg)}$ units of carbon-emitting energy inputs, and $x_{(i)}$ units of non-energy intermediate goods. Sectoral output 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. The Armington good specification allows us to assume that goods from different origin are only imperfect substitutes, hence with different substitutability between domestic and foreign output, and between different foreign regions (Armington, 1969). The general production structure is displayed in Figure 1.
Final consumption in each region is depicted by a representative household that maximises utility by spending her budget on consumption goods. The consumer's budget is determined by the consumer's income from selling his factor endowments on the market and from possible government transfers. Households are endowed with a fixed amount of labour and capital, which is mobile across sectors within regions but not across regions. As we are mainly interested in the effects of the behavioural shortcomings in the consumption of energy services, 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 analytical framework in the previous section. Accordingly, utility of the representative agent in region r is given by:

[5]For a general description of the World Input-Output Database (WIOD) CGE model, see Koesler and Pothen (2013).

$$u\left(s, x_{(eg)}, x_{(i)}\right) = \left[\alpha_{(s)} s^{\rho^{sz}} + \left(\alpha_{(eg)} x_{(eg)}^{\rho^{egi}} + \alpha_{(i)} x_{(i)}^{\rho^{egi}}\right)^{\frac{\rho^{sz}}{\rho^{egi}}}\right]^{1/\rho^{sz}} \tag{6}$$

The consumer'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 $x_{(i)}$ and the energy service s in region r. The respective share parameters are $\alpha_{(s)}$, $\alpha_{(eg)}$, $\alpha_{(i)}$ and the degree of substitutability in consumption between energy services and other consumption goods and between energy and non-energy goods is given by the respective substitution parameters ρ^{sz} and ρ^{egi}. The substitution parameters are related to the elasticity of substitution (e.g. σ^{egi}) through $\rho^{egi} = \frac{\sigma^{egi}-1}{\sigma^{egi}}$.

Within a CES function, we can adjust the substitutability among the consumed goods and thereby investigate the implications of possible relative changes in the composition of the consumption set. In the main scenarios of our model, utility is given as a Leontief composite of energy services and other consumption goods ($\sigma^{sz} = 0$).[6] An elasticity of substitution greater than zero in the top level enables us in later simulations to model a situation in which the household is able to shift the consumption to other consumption goods if she thinks energy service consumption is becoming more expensive.

As we are interested in the impacts of behavioural inefficiencies on consumption, we extend the model by an energy service module that describes the consumption of energy services as described in our analytical framework in section 2.1. Accordingly, energy service consumption in region r is described by the following CES function:

$$s\left(x_{(a)}, x_{(el)}\right) = \left[\alpha_{(a)} x_{(a)}^{\rho^{ela}} + \alpha_{(el)} \left(\theta_{(el)} x_{(el)}\right)^{\rho^{ela}}\right]^{1/\rho^{ela}}, \tag{7}$$

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. The degree of substitutability in the consumption of the energy service is given by the respective substitution parameters ρ^{ela}, which is related to the elasticity of substitution σ^{ela} through $\rho^{ela} = \frac{\sigma^{ela}-1}{\sigma^{ela}}$. Share parameters are given by $\alpha_{(el)}$ and $\alpha_{(a)}$.[7] The structure of the utility function is shown in Figure 2. The red dashed line indicates the new branches we added to the CGE model in order to incorporate the energy service consumption.

We further include the exogenous parameter $\theta_{(el)}$ as input productivity parameter. This parameter can be thought of as a *behavioural inefficiency* parameter in our simulations representing the inefficiencies in energy service consumption that might be due to various non-technical reasons. More specifically, households might possess only imperfect knowledge about how goods are most efficiently used in the consumption of energy services.[8] Therefore, a $\theta_{(el)} < 1$ implies that the household is using more energy than is actually needed for the energy service. In case there is no behavioural inefficiency $\theta_{(el)} = 1$ which means the household is consuming the energy service in the most efficient way. This allows us to incorporate behavioural productivity changes in our simulations. If the household fails to accomplish the most productive level in the consumption of energy service, she will always use too much energy, regardless of the direction of the price misperception.

[6] We follow Schenker et al. (2018) who assume that utility of the representative agent is defined as a Leontief composite of all final goods. This assumption prevents the consumers from shifting away from energy services if the energy service composite good becomes more expensive.

[7] New purchases of electrical appliances are combined with an existing appliance stock $x_{(astock)}$, assuming perfect substitutability.

[8] Examples of this would be cooking with a pot without putting a lid on it or driving a car at constant speed without shifting up into a more efficient gear. All these energy services might be consumed more efficient

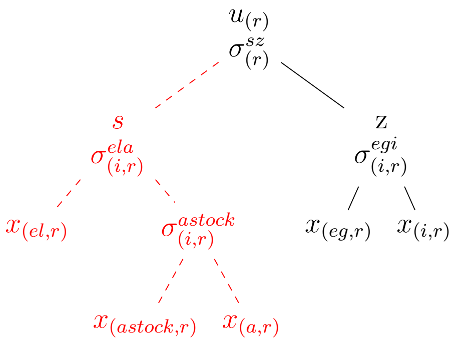


Figure 2: Household consumption structure

The result of the expenditure minimisation problem yields the energy service marginal costs for each region r

$$\widetilde{p_s}\left(p_{(a)}, \widetilde{p}_{(el)}\right) = \left[\alpha_{(a)} \left(\frac{p_{(a)}}{\alpha_{(a)}}\right)^{\frac{\rho^s}{\rho^s-1}} + \alpha_{(el)} \left(\frac{\widetilde{p}_{(el)}}{\alpha_{(el)}}\right)^{\frac{\rho^s}{\rho^s-1}} \right]^{\frac{\rho^s-1}{\rho^s}}, \tag{8}$$

where the perceived electricity price is given by $\widetilde{p}_{(el)}$. As in our analytical model, the resulting marginal energy service costs $\widetilde{p_s}$ are biased.

With regard to our research question, there are several crucial parameters. The most important parameter is the degree of misperception. As we want to take into account trade-offs in energy service consumption, we also need to account for sensitivity with regard to the respective elasticities of substitution. Including the input productivity parameter $\theta_{(el)}$ in the energy service consumption function allows us to look at the impact of a change in the input productivity of electricity in the presence of behavioural inefficiencies.

2.2.2 Data, Aggregation and Calibration

The CGE model is tailored to provide a maximum fit with data from 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.[9] The model differentiates up to 40 regions and a rest of the world region and features data from 35 sectors.

We are mainly interested in the consumption and production effects of the consumption of energy services in the presence of behavioural shortcomings. Therefore, we change the original aggregation structure of the basic WIOD CGE with regard to this aspect and reduce the sectoral disaggregation to 13 sectors. To account for the energy service consumption level, we use the region specific consumption data from the WIOD, assuming that all final demand goods from the sectors 'machinery' and 'electrical equipment' are combined with electricity. We further use the data from Federal Statistical Office Germany (2011) to account for good stocks of electric appliances to calibrate a more appropriate share parameter in the energy service consumption module. By using consumption data from AGEB (2012) and price data from BDEW (2017), we are able to separate electricity from gas and water supply of the original WIOD dataset. In our analysis, we further focus on the regions EU and Germany and create a rest of the world region that aggregates all the other regions. The aggregation scheme is displayed in Table 5 and Table 6 in Appendix A.1.

without switching to a more efficient technology.

[9]The year 2009 is the most recent year that comprises all data required, as the WIOD release from November 2016 does not cover industry energy use, CO_2 emissions and emissions to air.

Table 1: Scenarios

Scenario		Simulation Description
1	MP	Electricity price misperception between -50% and +50%
1.1	NMP	Negative electricity price misperception of -50%
1.2	PMP	Positive electricity price misperception of 50%
2	BE	Increase in the behavioural efficiency of 10% ($\theta_{(el)} = 1.1$)
3	SE	Increase in the elasticity of substitution in consumption ($\sigma^{sz}_{(GER)} = 0.5, 1.0, 1.2$)

We further consider short-run ($\sigma^{ela}_{(GER)} = 0.2$) and long-run ($\sigma^{ela}_{(GER)} = 0.4$) scenarios.

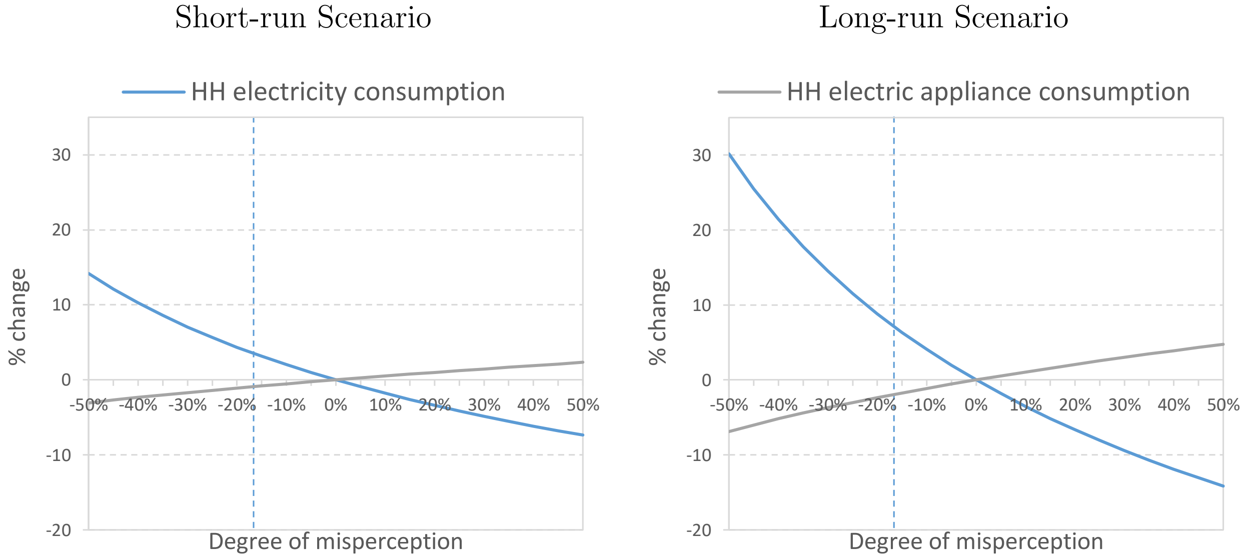
Substitution elasticities are taken from Koesler and Schymura (2012) who exploit the time series nature of the data and estimate substitution elasticities for all sectors included in the database. Armington elasticities required by the model are taken from GTAP8 (Hertel et al., 2014) and mapped to WIOD sectors.
As far as CO_2 emissions are concerned, the model distinguishes between energy related CO_2 emissions (arising due to the burning of fossil fuels) and process emissions (e.g. caused during the production of cement).[10] The shares of the fictive inputs vary depending on the type of accompanied energy good.[11]

2.2.3 Simulation Strategy

In this paper, we consider several scenarios that simulate households' electricity price misperceptions and behavioural efficiency improvements in energy service consumption. An overview of the sets of scenarios is displayed in Table 1.
We define a region's misperception of the regional electricity price to be the relative deviation of the median of the regional consumers' price perception from the actual average regional electricity price including taxes in the respective country. Due to the wide range of electricity price misperceptions across Europe (see Table 7 in Appendix A.1), we look at misperceptions in both directions, i.e. in the range between -50% and $+50\%$ of the real market price in our main scenarios (MP). For the representative German household in 2018 this range would imply a price perception between about 15 Cent/kWh and 45 Cent/kWh. By simulating this price perception range in the CGE framework, we are able to identify the main channels that are affected by the electricity price misperception.
Scenario 1.1 (NMP) and Scenario 1.2 (PMP) are special cases of the MP scenario and represent the extreme misperception values we simulate. In the NMP scenario we simulate a -50% electricity price misperception and in the PMP scenario we simulate a positive electricity price misperception of $+50\%$. Furthermore, the short-run adjustments in the demand for household appliances responding to a higher or lower misperception in the electricity price can be assumed to be lower than in the long-run. There might simply be a degree of inertia in the consumption response, but it can also be assumed that expensive new appliances like washing machines or televisions are purchased with the longer term view in mind, as these purchases are not every day decisions. We simulate this by accounting for a difference between short- and long-run elasticities between electricity and the electric appliance and assume a short-run substitution elasticity of 0.2 and a long-run substitution elasticity of 0.4 which a quite conservative assumption (see e.g. Fischer et al. (2017), Lecca et al. (2014)). An increase in the elasticity translates

[10] Emissions in the WIOD CGE model 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.
[11] See Koesler and Pothen (2013) for more information on the modelling of emissions in the WIOD model.

Figure 3: Relative change in energy service input demands (MP Scenario)



into facilitating the household to switch to a more efficient technology and thereby reduce its electricity demand. A higher elasticity of substitution between electricity and appliance however, also implies that in the case of a negative misperception where the household undervalues the electricity price, the household will buy less new appliances and consume more electricity compared to a situation without misperception.

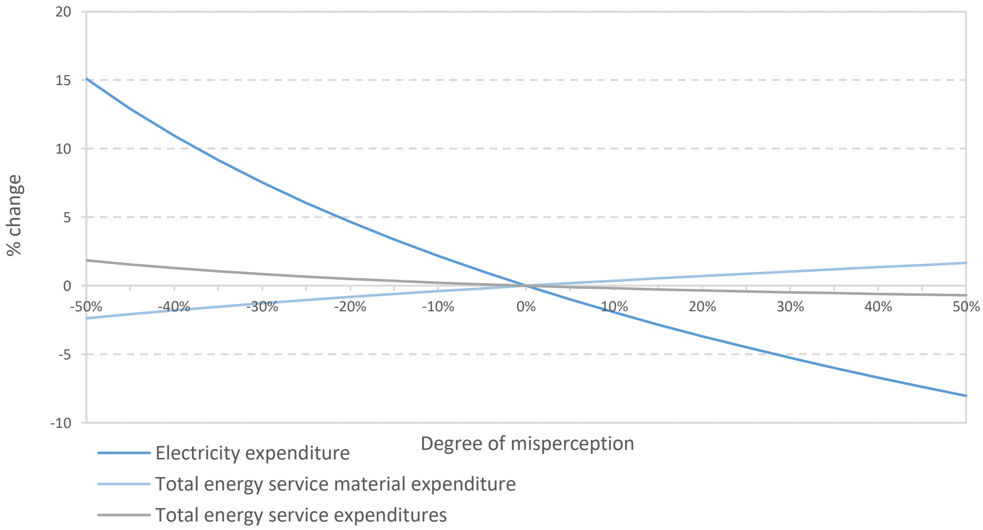
In the second scenario (BE), we look at a change in behavioural efficiency of the consumption of energy services in Germany, given by our model parameter $\theta_{(el)}$. This allows us to analyse another consumer behaviour that needs to be taken into account when looking at efficiency improvements in energy service consumption in the residential sector. By increasing $\theta_{(el)}$, we are able to simulate the impact of energy literacy improvements that reduce electricity use by households and do not require switching to another technology.

In a last step, we briefly consider the case of an increase in households willingness to shift their consumption from energy services to other consumption goods and vice versa. To accomplish that, we relax the the underlying Leontief assumption between energy services and other, non-electricity, consumption goods in the household utility function and allow for substitution across energy services and other goods in consumption. This is our third simulation (SE). The change in substitutability in this set of scenarios is combined with the previous scenarios to evaluate importance of this parameter on the model results.

3 Results

We first simulate a wide range of possible electricity price misperceptions in Germany and compare the results with the benchmark situation without a misperception. A change in electricity consumption depends on the direction of the misperception and is linked to the use of more or less energy efficient appliances. Figure 3 shows the importance of the trade-off or adjustment process in energy service consumption that is represented by the households' ability to substitute electricity for more energy efficient appliances. The dashed blue line depicts the median misperception in Germany that was found in the large survey sample conducted by Boogen et al. (2018). Notice that we do not allow the substitution between energy services and any other consumption good at this point. Due to that, our energy service consumption does not change by much as consumption is not shifted to other goods. Therefore, the main decision that the household is making is how she is going to consume this service.

Figure 4: Relative changes in the expenditure on energy services



Compared to a situation in which households are fully informed a negative misperception of 50% of the (real) market price, leads to an increase in electricity consumption by 14.18% and a reduction of 3.08% in purchases of new electric appliances (see Figure 3, 'Short-run Scenario'). As demand for energy services change with respect to the equilibrium quantities, the prices need to change in order to restore the equilibrium between demand and supply. A misperception of energy prices hence has a significant impact on households expenditure. Figure 4 shows short-run changes of energy services expenditure, which is made of the expenditure on new appliances and electricity. Total expenditure on new electric appliances decrease by 2.37%. A household that thinks the electricity price is 50% higher than the (real) market price will reduce its electricity consumption by 7.37% and increase its purchases of new electric appliances by 2.33%, increasing expenditure on appliances by 1.66%.[12]

A higher substitutability in the long-term more than doubles the effect of the price misperception in comparison to the short-term (see Figure 3, 'Long-run Scenario'). Misperceiving the electricity price to be 50% lower than it actually is leads to a 30.15% higher electricity consumption compared to the benchmark scenario with no misperception. It also results in a reduction of 6.88% in purchases of new electric appliances, diminishing expenditure on these appliances by 6.19%. If prices are misperceived to be 50% above their true level, households consume 14.17% less electricity and increase their electric appliance purchases by 4.77% and expenditure on the appliances by 4.13%.

The misperception in electricity prices also has an impact on the consumption of other goods. As we do not allow for a substitution between other consumption goods and energy services at this point, possible changes in other consumption goods equals the relative change in energy service consumption, which is of course much lower in absolute terms. Figure 5 displays the impact of price misperceptions for various elasticities of substitution in the consumption of the energy service ($\sigma^{ela}_{(GER)} = \{0, 0.1, 0.2, 0.4\}$). We observe that a negative electricity price misperception can lead to a decrease or an increase in the consumption of other goods depending on the ability or ease to substitute more electricity for appliances. We see a turning point in the increase in consumption of other goods for elasticities above 0.2 for a negative electricity price misperception above about 25%. The consumption change of other goods compared to the benchmark becomes negative for the long-term elasticity ($\sigma^{ela}_{(GER)} = 0.4$) in case of a positive misperception but also in case of a negative misperception greater than 47%.

[12]The elasticities of electricity demand are similar to those in Deryugina et al. (2017) and Alberini and Filippini (2011).

Figure 5: Relative change in other consumption

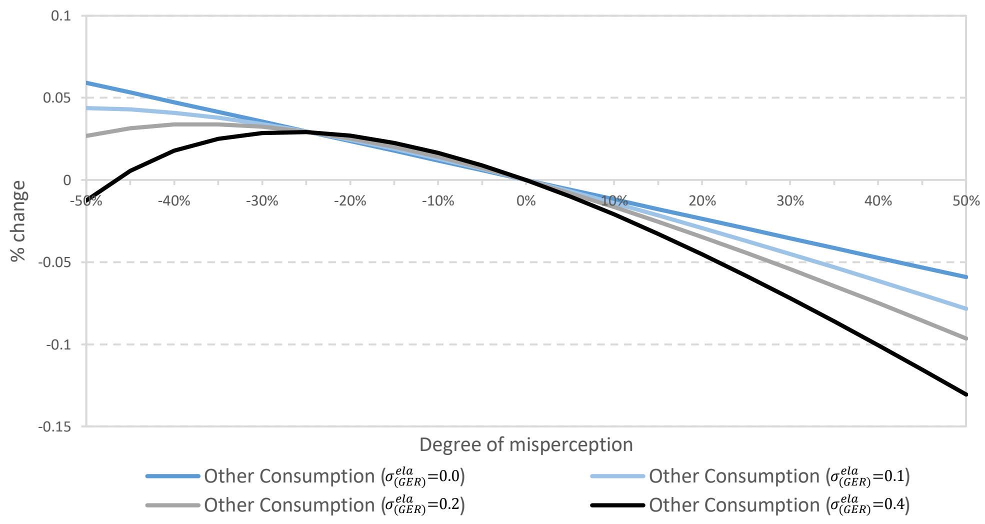


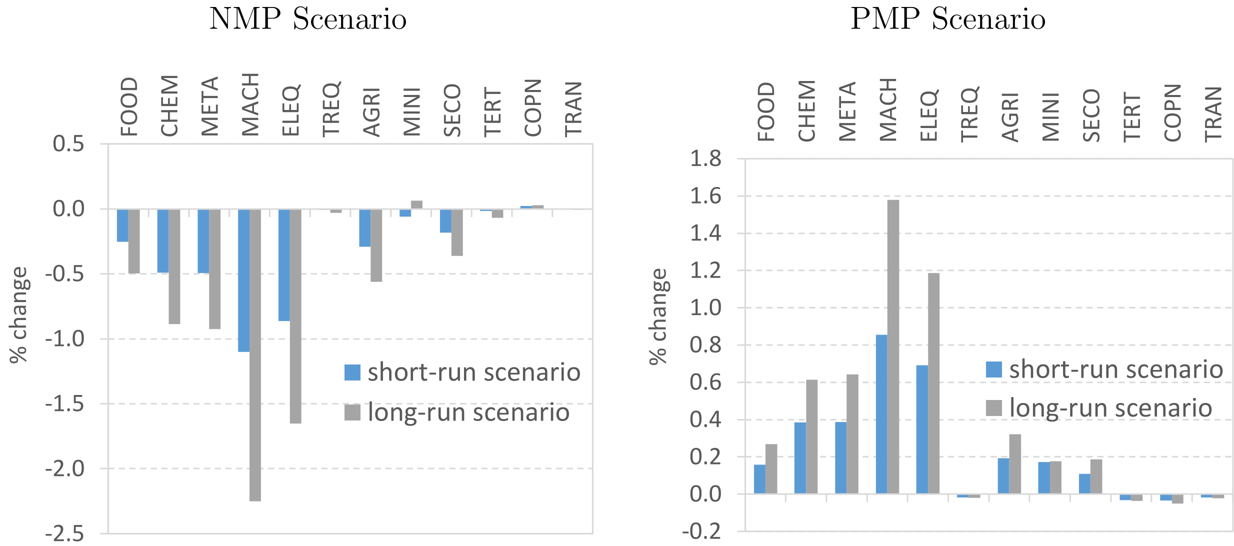
Table 2: Changes in key variables and macroeconomic indicators in Germany [%]

	NMP Scenario[b]		PMP Scenario[c]		BE Scenario[d]	
	SR[a]	LR[a]	SR[a]	LR[a]	SR[a]	LR[a]
GDP	-0.05	-0.15	-0.03	-0.03	0.14	0.13
Exports	-0.43	-0.77	0.33	0.54	0.01	-0.05
Imports	-0.00	-0.02	0.01	0.03	-0.02	-0.02
CO_2 emissions	2.33	4.96	-1.19	-2.31	-1.22	-0.95

[a] SR: short-run; LR: long-run
[b] NMP: Negative electricity price misperception of 50%
[c] PMP: Positive electricity price misperception of 50%
[d] BE: Increase in the behavioural efficiency of 10%

The CGE model allows us to look at the impact of price misperceptions on the supply side of the market and how changes in electricity consumption of the households affect CO_2 emissions in the economy. For the sake of clarity, we now consider two misperception scenarios. In the first scenario, we simulate a negative electricity price misperception of 50% (NMP scenario). In the second scenario, we simulate a positive misperception (PMP scenario), i.e. households think the electricity price is 50% higher than it actually is. Before we look at the different production sectors, we present some key macroeconomic indicators in Table 2.
Compared to a situation without a electricity price misperception, in the short-run NMP scenario, gross domestic product (GDP) in Germany decreases by 0.05%, household final consumption and CO_2 emissions increase by 0.03% and 2.33% respectively. In the long-run GDP, household final consumption and CO_2 emissions decrease by 0.15%, 0.01% and 2.31% respectively.
Just like in the case of a negative misperception, the change that is due to a misperception in a positive direction is rather small. Compared to a situation without any misperception, GDP and final consumption by households decrease by 0.03% and 0.10% respectively in the short-run scenario when households think the electricity price is 50% higher than it actually is (PMP scenario). In the long-run GDP decreases by 0.03% and household final consumption decreases by 0.13%. CO_2 emissions decrease by 1.19% in the short-run and by 2.31% in the long-run PMP scenario.
The industry mostly affected by the behavioural shortcomings of the consumer is the electricity

Figure 6: Production change compared to benchmark



sector.[13] In the NMP scenario, electricity output increases by 4.58% in the short-run and by 9.75% in the long-run. In the PMP scenario, electricity production in Germany is reduced by 2.36% (4.55%) in the short-run (long-run) compared to a situation without electricity price misperception. As changes in the electricity demand lead to price changes, also other production sectors are affected. Figure 6 shows the relative changes in production of the other production sectors compared to a situation without a misperception for the two scenarios in the short- and long-run.

In the PMP scenario, the machinery sector (MACH) and electrical equipment (ELEQ) sector in Germany increase their output by 1.58% and 1.19% respectively in the long-run, compared to a situation without a price misperception. Furthermore, imports of electrical equipment increase by 0.97% in Germany.

The impact of a misperception of the electricity price in Germany on the European economy are rather small. European exports of electrical equipment used as intermediate and final goods decrease by 0.01% in the short-run and increase by 0.03% in the long-run in the NMP scenario, whereas total EU machinery exports decrease by about 0.03% in the short- and long-run. In the PMP scenario, European electrical equipment (machinery) exports increase by 0.03% (0.03%) in the short-run and by 0.02% (0.04%) in the long-run. European energy service consumption is not affected by electricity price misperceptions in Germany as in all scenarios changes in consumption are below 0.01%.

In the BE scenario, we increase the behavioural efficiency in the consumption of energy services and analyse the changes in electricity and electric appliance demand in the absence of electricity price misperceptions. The behavioural efficiency shock reduces the electricity that is needed to provide the energy service. As before, we do not allow for a substitution between energy services and other consumption goods. The increase in behavioural efficiency results in increasing consumption of energy services and electric appliances. A 10% increase in behavioural efficiency in the consumption of the energy service makes the households consume 0.14% more energy services compared to a situation without the behavioural efficiency improvement in the short- and long-run. The energy service level and the purchases of new appliances (+0.20%) are increasing compared to the benchmark situation in the short-run but electricity use is decreasing by 7.31%. The efficiency improvement thus reduces electricity use, but as energy

[13] As the changes are too large compared to the other sectors, the electricity sector is not shown in the figure for the sake of clarity.

Table 3: Short- and long-run changes in consumption (BE Scenario) [%]

	Short-run	Long-run
Energy services	0.14	0.14
Electricity	-7.31	-5.62
Electric appliances	0.20	-0.34

service consumption is increasing the gains from that improvement are reduced, a phenomenon commonly referred to as *rebound effect* (Chan and Gillingham, 2015). In the long-run, the behavioural efficiency improvement increases energy service consumption by 0.14%. Electricity use is decreasing by 5.62% and we observe a relative change in new electric appliance of -0.34% compared to the benchmark situation.

As the increase in behavioural efficiency is modelled as a costless productivity improvement, total welfare will increase in general equilibrium. However, it is interesting to see that in the short-run, a 10% increase in behavioural efficiency leads to almost the same reduction in electricity demand (7.31%) as in our electricity price misperception simulation where consumers think electricity is 50% more expensive than it actually is (7.37%). Unlike it is the case for the positive electricity price misperception, in the long-run the effect of the behavioural efficiency improvement is reduced. A 10% increase in efficiency reduces electricity demand by 5.62% in the long-run whereas a positive misperception of 50% reduces electricity demand by 14.17%. The impact on electric appliance purchases are greater in the case of price misperceptions as consumers are switching to more or less efficient technologies dependent on the direction of the price misperception as described above. In the case of the behavioural efficiency improvement, relative changes in electric appliance purchases are very small, i.e. 0.20% in the short-run and -0.34% in the long-run scenario.

In order to understand the overall social welfare implications, it would be necessary to take into account externalities in our scenarios. As the demand for electricity changes throughout the whole economy, also CO_2 emission levels change. In the short-run (long-run), total CO_2 emissions in Germany increase by 2.33% (4.96%) in case of a negative electricity price misperception of 50% and decrease by 1.19% (2.31%) when the electricity price is assumed to be 50% higher than it actually is. In the NMP scenario (PMP scenario), CO_2 emissions that are caused by the electricity sector increase (decrease) by 4.59% (2.37%) in the short-run and increase (decrease) by 9.77% (4.56%) in the long-run. The change in total CO_2 emissions in Germany that result from a 10% increase in behavioural efficiency amounts to -1.22% (-0.95%) in the short-run (long-run), where the electricity sector is decreasing its CO_2 emissions by 2.40% in the short-run and 1.85% in the long-run.

In a last step, we relax the Leontief assumption and present the results of a situation in which consumers are able and willing to shift away from energy services if the energy service composite good becomes more expensive. As the Leontief assumption prevents households from substituting energy services for other consumption goods, we see amplified effects in the energy service consumption if this substitution becomes easier. We conduct a sensitivity exercise with respect to the elasticity of substitution and depict the results for four different elasticities in the NMP and the PMP scenario in Table 4.[14]

An increase in behavioural efficiency of 10% both in the short- and long-run increases energy service consumption and the consumption of other goods. However, when we gradually increase the elasticity of substitution between energy services and other consumption goods in the utility function, households are increasing their energy service consumption. Compared to the main scenarios without substitution in consumption, in the NMP scenario, energy service

[14] Long-run results are displayed in Table 8 in Appendix A.1.

Table 4: Short-run changes in consumption and other key variables in Germany [%]

	NMP[a]				PMP[b]			
	$\sigma^{sz}_{(GER)}$							
	0.00	0.50	1.00	1.20	0.00	0.50	1.00	1.20
Energy services	0.03	1.11	2.13	2.52	-0.10	-1.04	-1.92	-2.25
Electricity	14.19	15.46	16.64	17.10	-7.38	-8.27	-9.10	-9.41
Electric appliances	-3.08	2.71	8.12	10.20	2.33	-2.76	-7.47	-9.25
Other consumption	0.03	-0.39	-0.78	-0.92	-0.10	0.26	0.60	0.73
CO_2 emissions	2.33	2.59	2.84	2.93	-1.19	-1.39	-1.58	-1.64

Short-run scenario: $\sigma^{ela}_{(GER)} = 0.2$
[a] NMP: Negative electricity price misperception of 50%
[b] PMP: Positive electricity price misperception of 50%

consumption is increasing from 0.03% up to 2.52% in the short-run. In the PMP scenario, we observe that consumers are increasingly shifting away from energy service consumption by reducing their purchases of new appliances and also electricity consumption. In the BE scenario, an elasticity of substitution above one leads to a reduction in consumption of other goods as consumers are shifting their consumption to energy services. That also results in a reduction in electricity consumption savings (i.e. a larger rebound effect).

4 Conclusion

This paper extends the analysis of households' energy service consumption by simulating electricity price misperceptions and behavioural inefficiencies in a CGE model. We conclude that the impact of potential policies aimed at increasing households' energy efficiency will crucially depend on whether households actually observe prices in an unbiased fashion. Our simulations further indicate that households ability to process information and modify their expenditure structure accordingly is a decisive factor for the success of efficiency improvements in their homes.

We find that misperceived electricity prices change the way energy services are consumed but do not affect its overall consumption level by much. With respect to the rest of the economy in Germany and the EU, changes in production as well as consumption remain rather small for those goods that are only indirectly affected by the misperception of electricity prices. Confronted with the real market price, energy efficiency will increase when households perceived the electricity price to be lower than it actually is. Providing information on electricity prices can therefore have a positive effect on electricity demand reductions if households are able to identify possible trade-offs in their energy service consumption. Households that are aware of alternative and more efficient electric appliances can reduce electricity consumption by switching to more efficient technologies. We further show in our behavioural efficiency simulations, that improving the knowledge on how to save energy using appliances more efficiently has a greater effect in the short-run. If households are able to adjust their behavioural efficiency in energy service consumption over the long term they might refrain from buying more energy efficient technologies. As the electricity sector is mostly affected by the price misperceptions and behavioural inefficiencies of households, electricity production levels and CO_2 emissions are also higher if prices are perceived to be lower than they actually are.

Theses results also hold true if households are able and willing to shift their consumption from energy services to other consumption goods or vice versa. The sensitivity analysis shows that when we relax the Leontief assumption in the consumer's utility function and allow for substitution across goods in consumption, the effect on electricity demand levels and CO_2 emissions increases in magnitude. In the case of electricity price misperceptions, allowing for substitution in consumption reverses the effects of electric appliance purchases and other consumption as households increase energy service consumption in the case of negative price misperceptions.

However, when consumers perceive the electricity price to be higher than it actually is, providing actual cost information can turn out to be counterproductive in terms of energy demand reductions and CO_2 emissions as households might realise that they pay less than they expected. Therefore, from a private perspective households might invest too much in energy efficiency, but from a environmental point of view this over-investment could be beneficial. Potential co-benefits that result from reduced energy demand like health benefits trough better air quality will additionally have economy-wide implications through public health spending.

In order to understand the overall social welfare implications, it is necessary to take into account externalities. Building on the research presented in this paper, future studies should investigate the overall welfare effects of misperceived energy prices and behavioural shortcomings in energy service consumption. Furthermore, other energy services such as heating or private transportation and possible trade-off between energy services can be analysed. Given that electricity price misperceptions vary across countries, assessing their joint impacts on total European electricity consumption is a key aspect for future research. Analysing these aspects, however, require a considerable extension of existing models and data.

References

AGEB (2012). Energy Balance for the Federal Republic of Germany 2009, https://ag-energiebilanzen.de/7-1-Energy-Balance-2000-to-2015.html. (Accessed 8 November 2018).

Alberini, A. and Filippini, M. (2011). Response of residential electricity demand to price: The effect of measurement error, *Energy economics* **33**(5): 889–895.

Allcott, H. (2010). Beliefs and Consumer Choice, *Manuscript: New York University* .

Allcott, H. (2013). The welfare effects of misperceived product costs: Data and calibrations from the automobile market, *American Economic Journal: Economic Policy* **5**(3): 30–66.

Allcott, H. and Rogers, T. (2014). The short-run and long-run effects of behavioral interventions: Experimental evidence from energy conservation, *The American Economic Review* **104**(10): 3003–3037.

Allcott, H. and Taubinsky, D. (2015). Evaluating behaviorally motivated policy: experimental evidence from the lightbulb market, *American Economic Review* **105**(8): 2501–38.

Armington, P. S. (1969). A theory of demand for products distinguished by place of production, *Staff Papers* **16**(1): 159–178.

Attari, S. Z., DeKay, M. L., Davidson, C. I. and De Bruin, W. B. (2010). Public perceptions of energy consumption and savings, *Proceedings of the National Academy of sciences* **107**(37): 16054–16059.

BDEW (2017). BDEW-Strompreisanalyse, Haushalte und Industrie, https://www.bdew.de/service/daten-und-grafiken/bdew-strompreisanalyse/. (Accessed 8 November 2018).

Blasch, J., Boogen, N., Filippini, M. and Kumar, N. (2017). Explaining electricity demand and the role of energy and investment literacy on end-use efficiency of Swiss households, *Energy Economics* .

Boogen, N., Daminato, C. and van der Werff, E. (2018). PENNY - Psychological, Social and Financial Barriers to Energy Efficiency: Large sample survey.

Brounen, D., Kok, N. and Quigley, J. M. (2013). Energy literacy, awareness, and conservation behavior of residential households, *Energy Economics* **38**: 42–50.

Chan, N. W. and Gillingham, K. (2015). The microeconomic theory of the rebound effect and its welfare implications, *Journal of the Association of Environmental and Resource Economists* **2**(1): 133–159.

DellaVigna, S. (2009). Psychology and economics: Evidence from the field, *Journal of Economic literature* **47**(2): 315–72.

Deryugina, T., MacKay, A. and Reif, J. (2017). The long-run dynamics of electricity demand: Evidence from municipal aggregation, *Technical report*, National Bureau of Economic Research.

ElCom (2017). Electricity tariffs, https://www.elcom.admin.ch/elcom/en/home/topics/electricity-tariffs.html. (Accessed 8 November 2018).

Eurostat (2017). Final energy consumption by sector, https://ec.europa.eu/eurostat/statistics-explained/index.php/Consumption_of_energy. (Accessed 8 November 2018).

Eurostat (2018). Electricity price statistics: online data codes: nrg_pc_204 and nrg_pc_205, https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics. (Accessed 8 November 2018).

Federal Statistical Office Germany (2011). WISTA Wirtschaft und Statistik.

Figus, G., Swales, J. K. and Turner, K. (2017). Can a Reduction in Fuel Use Result from an Endogenous Technical Progress in Motor Vehicles? A Partial and General Equilibrium Analysis, *Discussion paper* .

Fischer, C., Preonas, L. and Newell, R. G. (2017). Environmental and Technology Policy Options in the Electricity Sector: Are We Deploying Too Many?, *Journal of the Association of Environmental and Resource Economists* **4**(4): 959–984.

Gerarden, T. D., Newell, R. G. and Stavins, R. N. (2017). Assessing the energy-efficiency gap, *Journal of Economic Literature* **55**(4): 1486–1525.

Harding, M. and Hsiaw, A. (2014). Goal setting and energy conservation, *Journal of Economic Behavior & Organization* **107**: 209–227.

Hertel, T., McDougall, R., Narayanan, B. and Aguiar, A. (2014). GTAP 8 Data Base Documentation - Chapter 14 Behavioral Parameters , *Center for Global Trade Analysis, West Lafayette, USA* .

Hunt, L. C. and Ryan, D. L. (2015). Economic modelling of energy services: Rectifying misspecified energy demand functions, *Energy Economics* **50**: 273–285.

Jaffe, A. B. and Stavins, R. N. (1994). The energy-efficiency gap - What does it mean?, *Energy policy* **22**(10): 804–810.

Koesler, S. and Pothen, F. (2013). The Basic WIOD CGE Model: A computable general equilibrium model based on the World Input-Output Database, *Technical report*, ZEW-Dokumentation.

Koesler, S. and Schymura, M. (2012). Substitution Elasticities in a CES Production Framework-An Empirical Analysis on the Basis of Non-Linear Least Squares Estimations.

Lecca, P., McGregor, P. G., Swales, J. K. and Turner, K. (2014). The added value from a general equilibrium analysis of increased efficiency in household energy use, *Ecological economics* **100**: 51–62.

Schenker, O., Koesler, S. and Loeschel, A. (2018). On the Effects of Unilateral Environmental Policy on Offshoring in MultiStage Production Processes, *Canadian Journal of Economics/Revue canadienne d'conomique* **51**: 1221–1256.

Sorrell, S. and Dimitropoulos, J. (2008). The rebound effect: Microeconomic definitions, limitations and extensions, *Ecological Economics* **65**(3): 636–649.

Taubinsky, D. (2013). From intentions to actions: A model and experimental evidence of inattentive choice, *Working Paper* .

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R. and Vries, G. J. (2015). An illustrated user guide to the world input–output database: the case of global automotive production, *Review of International Economics* **23**(3): 575–605.

A Appendix

A.1 Tables

Table 5: 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 6: 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

Table 7: Electricity price misperception

Country	Average[a] [EUR/kWh]	Median[a] [EUR/kWh]	Actual[b] [EUR/kWh]	Misperception [%]
Switzerland	0.22	0.16	0.18	−5.47%
Netherlands	0.35	0.19	0.16	+18.75%
Italy	0.35	0.20	0.21	−4.76%
Germany	0.26	0.25	0.30	−16.67%

[a] Source: Own calculations based on Boogen et al. (2018).
[b] Source: Eurostat (2018), ElCom (2017).

Table 8: Long-run changes in consumption and other key variables in Germany [%]

	NMP[a]				PMP[b]			
	$\sigma^{sz}_{(GER)}$							
	0.00	0.50	1.00	1.20	0.00	0.50	1.00	1.20
Energy services	-0.01	1.17	2.27	2.70	-0.13	-1.06	-1.91	-2.24
Electricity	30.16	31.76	33.27	33.84	-14.17	-15.00	-15.77	-16.06
Electric appliances	-6.88	-0.64	5.20	7.44	4.77	-0.23	-4.85	-6.61
Other consumption	-0.01	-0.46	-0.89	-1.05	-0.13	0.22	0.55	0.68
CO_2 emissions	4.96	5.29	5.69	5.71	-2.31	-2.49	-2.67	-2.73

Short-run scenario: $\sigma^{ela}_{(GER)} = 0.4$
[a] NMP: Negative electricity price misperception of 50%
[b] PMP: Positive electricity price misperception of 50%