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Rebound effects in German residential heating: Do ownership and income matter?

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Abstract

In this paper, by using panel data and a fixed effects model, we estimate the direct rebound effect related to space heating in German residential households. The data used are from a representative repeated survey among some 11,000 households in Germany provided by the German Institute of Economic Research (DIW Berlin). We find that for the size of the direct rebound effect, i.e. the amount of energy consumption "taken back" when energy efficiency rises, income and ownership matter significantly. The estimated rebound effects for the different household groups range between 12% for owners (income class "all") and 49% for tenants (income class "low"). Tenants are found to have much higher rebound effects. Higher-income owner households have a slightly higher rebound than lower income households (14% vs. 13%), whereas for tenant households the outcome is reversed (31% vs. 49%). We conclude that energy rebound effects in the residential sector should be tackled in energy policy making in a differentiated way, and certainly not ignored in energy efficiency policies.

Key words: Rebound effect; SOEP panel; fixed effects; energy efficiency

JEL classification: D12, Q41;

1. Introduction

Climate change mitigation requires a reduction in (fossil) energy consumption and CO_2 emissions in all sectors of the economy. To tackle this challenge, among other decarbonizing

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action, rigorous energy efficiency improvements are required. The implementation of measures to raise energy efficiency calls for sound energy policy design and a better understanding of the relevance of both rebound and habit persistence effects.

The European Commission has implemented a Directive in 2002 concerning energy efficiency of buildings (EU Directive 2002/91/EC; CEC 2002), the regulations of which have to be implemented by the member states into national legislation. In Germany, where space heating accounts for about one third of total final energy consumption, and thus a major share, a revised Energy Saving Ordinance (EnEV 2009) has recently entered into force, and the next revision to be implemented in 2012 is currently under way. Residential households have the largest share in energy consumption for space heating (in Germany ca. 30%). Especially existing buildings have a substantial economic potential for energy savings.

Generally speaking, after introducing an energy efficiency measure, a change in the residential households' energy consumption behavior can reduce the energy savings potential expected based on engineering-economic calculations alone. This effect is known as "rebound effect" (Khazzoom, 1980; Brookes, 1990) and, if larger than unity, can even lead to an increase in energy consumption as a result of energy efficiency improvements, referred to as "backfire" or the "Khazzoom-Brookes postulate" (Saunders, 1992), which would make energy efficiency policies even counterproductive. In the literature, various types of rebound are distinguished (direct, indirect, economy-wide; cf. Sorrell and Dimitropoulos, 2008). According to our literature review reported in section 2, comparable studies on the rebound effect in residential heating for other countries than Germany range from some 20-45%. Up to now, however, empirical evidence on the rebound effect in German households is scarce, and a distinction between homeowners and tenants is still lacking.

In this paper, we estimate the direct rebound effect related to space heating in German residential households using a fixed effects model, and explicitly account for the relevance of ownership vis-à-vis tenancy on the one hand, and of disposable income on the other hand. The data used are from a representative repeated panel survey (SOEP) among some 11,000 residential households in Germany, provided by the German Institute of Economic Research (DIW Berlin). The data sets for owners and tenants, respectively, are additionally split by income groups (all, low, high), thus enabling to gain some additional insights from the analysis.

We find that for the size of the direct rebound effect, i.e. the amount of energy consumption "taken back" when energy efficiency rises, income and ownership matter significantly. The estimated rebound effects range between 12% for owners and 49% for tenants (low income class). In other words, the main results from our study suggest that only between 51% and 88% of the energy saving potentials in the German residential sector could actually be realized, calling for a dedicated policy to mitigate the rebound effect in energy efficiency policy-making. Compared to other studies without panel data, our results are quite similar. The distinction between homeowners and tenants, to the best of our knowledge, is an original contribution of our panel econometrics rebound research. From the study, we can conclude that effective energy- and climate policy-making does not only depend on the technical boundary conditions, but also on behavioral change as a reaction to energy efficiency improvements. On the one hand, such improvements have the potential to reduce their energy consumption further, while, on the other hand, they can have negative consequences due to the rebound effect.

The remainder of this paper is organized as follows. Section 2 reviews the related literature. Section 3 contains alternative definitions of the rebound effect, Section 4 introduces the model specification used. Section 5 contains a description of the data and Section 6 the results obtained. Section 7 summarizes and concludes.

2. Related literature

In order to enable a comparison of the results, the econometric studies are classified by aggregation level, static or dynamic model, type of data, model structure, functional form and estimation method.[1] In this section, we review some econometric studies on the rebound effect for space heating in residential households that are similar to the present study regarding its categorization. For reasons of comparability of these studies with our study we especially put emphasis on similarities with respect to the level of aggregation of the data used, the focus on the household sector, and the definition of the rebound effect adopted.

Haas and Biermayr (2000) use time series analysis for estimating the rebound effect for space heating in Austria for the period 1970 until 1998. The simple econometric model includes, apart from the energy price, also heating degree days and effective consumption expenditures as further explanatory variables. The real energy price is an average from weighted fuel prices. The econometric analysis estimates the rebound effect to be about 30%. Apart from time series econometrics, the authors use complementary approaches to estimate the rebound effect that are very different in their categorization from the present study. Overall, the various approaches used yield rebound estimates in the range from 20-30%.

[1] For a detailed description of the categories see Sorrell and Dimitropoulos (2007: 24-39).

Nesbakken (2001) estimates the energy consumption for space heating in Norway by means of a discrete-continuous approach. To this end, the choice of heating technology is modeled/estimated in a first stage. Residential households choose between electricity-only, electricity and oil, electricity and wood or a combination of all three fuels. In a second stage, energy consumption is modeled and estimated. As in the present study, aside from energy price and income of the households, also the size of the households, heating degree days and the age of the buildings are included as explanatory variables in the model. Nesbakken employs in her study cross-sectional data of a sample of 551 Norwegian households in the year 1990. The price elasticities for the determination of the rebound effect are based on changes in average energy prices and are determined separately for each individual heating technology. The results range from -0.15 for the combination of all three fuels to -0.55 for electricity-only heating. The average price elasticitiy of all households suggests a rebound effect of 21%.

Guertin et al. (2003) report results, among others, for the rebound effect of space heating in Canada. In their study they use cross-sectional data for 440 households for the year 1993. In an econometric model for energy consumption, the explanatory variables include energy price, income of the households and heating degree days, but also additional regressors on technical information of the living area (e.g. room temperature, total and heated area and number of floors, doors and windows). The rebound effect estimated in the form of price elasticities range from 34% for high income classes to 51% for low income classes. The rebound on average for the sample lies at around 43%. With the help of a frontier analysis Guertin et al. additionally estimate the energy efficiency of water heaters and stoves. Another rebound effect is estimated by including this information for energy efficiency improvements, yielding an average rebound effect of 39%. High income classes exhibit a lower value at 29%, compared to low income classes at 47%.

The range of values for the rebound effects from these studies range on average from 21-43%, enabling a comparison with the results obtained from the present study. There are several commonalities among the studies reviewed with regard to the framework conditions considered. Still, the results are only comparable with the present study to the extent that differences in the framework conditions are taken care of.

3. The Rebound Effect

In order to determine the existence and the magnitude of the direct rebound effect, some basics and knowledge of the influencing factors are needed, which is the purpose of the following subsection.

3.1 Energy application, energy efficiency and the direct rebound effect

The direct rebound effect for some energy service, such as space heating in residential households, results from the estimated technical energy savings minus the actual amount of energy saved, after introduction of measures to raise energy efficiency (Herring, 2009: 4). Hence the computation of the rebound effect requires a comparison of energy consumption before and after the introduction of the efficiency measure. As consumers do not reap utility directly from the consumption of energy resources, the computation of energy consumption requires an understanding of the *demand for energy services*.

Specifically, energy demand (*E*) can be derived from the demand for energy services (*ES*). For instance, energy demand for gasoline depends on the intensity of driving a car. Almost all energy services require a certain form of energy, albeit the share of energy cost in the total cost for a specific energy demand may vary greatly (Sorrell and Dimitropoulos, 2007: 4).

Useful energy (*S*) is an important characteristic of an energy service. *S* can be measured by various thermodynamic or physical indicators. The right choice of indicators depends on the system considered, the purpose of the analysis and the available data base (Patterson, 1996: 377-390). For instance, useful energy in the case of individual car mobility can either be measured as vehicle miles, person-miles, or the (less common) ton-miles.

Apart from useful energy further characteristics (*A*) can exist, that together constitute an energy service and that can be combined with *S* in many different ways. For instance, cars differ with respect to their velocity and comfort, whereas the basic purpose of transporting people is fulfilled by all of them (Sorrell et al., 2009: 1357).

The *household production model* of Becker (1965) contributes to a better understanding of the demand for energy services. The framework describes three trade-offs of consumers and producers in consuming energy services. It helps to balance between useful work and the other characteristics of energy demand. Furthermore, there is a trade-off between energy, capital, other consumer goods and time in the “production” of an energy service. The third trade-off is between the consumption of different energy services (Sorrell und Dimitropoulos, 2007: 6).

The correct functioning of an energy service is guaranteed by the provision of an energy service, which requires input factors, such as labor, materials, and energy. The relevant energy system for the heating of households can be thought of in the form of radiators, heating pipes, a boiler, building substance, isolation, glazing of the house etc. (Sorrell et al., 2009: 1357).

The required energy efficiency of a system (ε) required for the computation of the rebound effect is the ratio between useful work (S) and energy demand (E):

$$\varepsilon = \frac{S}{E}. \tag{1}$$

Depending on the system boundary, energy efficiency can then be defined in various ways, as the following exposition shows (cf. Sorrell et al., 2009: 1357).

3.2 Definition of the direct rebound effect via elasticities

The rebound effect can be defined by *elasticities of energy efficiency*. Its mechanism can be defined as the impact on the cost of useful energy. The energy costs of useful work (P_S) are part of the total cost of useful work (P_{Total}) and defined as follows (Sorrell and Dimitropoulos, 2007: 6):

$$P_S = \frac{P_E}{\varepsilon}. \tag{2}$$

The energy price is denoted by P_E. Total costs (P_{Total}) include, apart from the energy costs, additionally annual capital cost (P_K), maintenance cost (P_M) and the variable cost (P_V) (Sorrell and Dimitropoulos, 2007: 6):

$$P_{Total} = \frac{P_E}{\varepsilon} + P_K + P_M + P_V. \tag{3}$$

The realization of an energy efficiency improvement raises the value of the energy efficiency (ε), the energy costs of useful work (P_S) decrease and, therefore, also the total costs (P_{Total}). Consumers will demand useful work (S) by means of a more intensive use of the energy-using capital stock. The change in energy consumption will then be smaller than the change in energy efficiency ($\Delta E/E < -\Delta\varepsilon/\varepsilon$). In the absence of a rebound effect, S remains unchanged and E is reduced proportionally to the improvements in energy efficiency ($\Delta E/E = -\Delta\varepsilon/\varepsilon$) (Sorrell and Dimitropoulos, 2007: 6).

However, apart from these price effects we also have to consider other influencing factors (Sorrell et al., 2009: 1357). For instance the level of the rebound effect can also be influenced by *saturation effects*. If consumption of a particular energy service rises, the rebound effect should diminish as a consequence. The reason is the decreasing marginal utility of an additional consumption of an energy service. For instance, after an energy efficiency improvement of the heating system in a residential household we would expect a decrease in the rebound effect, the more the indoor temperature is aligned to the most comfortable indoor temperature. Milne and Boardman (2000: 422) come to the conclusion that the rebound effect in low-income groups of society is larger, as these are typically further away from the most comfortable living space temperature.

A source for high rebound effects can be marginal consumers, that only through cost reductions achieved by energy efficiency are given an opportunity or the desire to consume a certain energy service (Sorrell et al., 2009: 1357). Especially in developing countries there is thus a possibility of large rebound effects (Roy, 2000). For the case of space heating in Germany the impact of the marginal consumers can be expected to be unimportant, as even the lowest income groups have access to heated living space due to the social security system.

The definition of the direct rebound effect by energy efficiency elasticities are provided in the following section 3.2.1. The subsequent section then introduces the definition and restrictions of rebounds via price elasticities. For a detailed elaboration of the derivation of the definitions see Sorrell und Dimitropoulos (2007: 6-12).

3.2.1 Definition of energy efficiency elasticities

The rebound effect can be calculated by the following two energy efficiency elasticities (Sorrell and Dimitropoulos, 2007: 6f):

$\eta_\varepsilon(E)$: elasticity of energy demand (*E*) with regard to energy efficiency (ε)

$\eta_\varepsilon(S)$: elasticity of useful energy demand (*S*) with regard to energy efficiency

From the equation $\varepsilon = S/E$, we can derive the following relationship (Sorrell and Dimitropoulos, 2007: 7):

$$\eta_\varepsilon(E) = \eta_\varepsilon(S) - 1. \quad (4)$$

Equation (4) defines the direct rebound effect by energy efficiency elasticities (Sorrell and Dimitropoulos, 2007: 7). The elasticity $\eta_\varepsilon(S)$ is commonly used for the measurement of the direct rebound effect. If an elasticity $\eta_\varepsilon(S) = 0$ and thus $\eta_\varepsilon(E) = -1$ is measured, there is no rebound effect, and the actual energy savings are equal to the technical predictions. In case of a positive rebound effect the elasticities take values of $\eta_\varepsilon(S) > 0$ and $0 > \eta_\varepsilon(E) > -1$, respectively. Backfire implies elasticities of $\eta_\varepsilon(S) > 1$ and $\eta_\varepsilon(E) > 0$. The size of the rebound effect is expressed in percent. A rebound effect of 20%, for instance, means that the predicted technical energy saving potential is realized at 80%. Elasticities in this case would take values of $\eta_\varepsilon(S) = 0.2$ and $\eta_\varepsilon(E) = -0.8$. The energy savings loss can be attributed to the increased demand for useful energy (Sorrell et al., 2009: 1359).

3.2.2 Definition by price elasticities

The availability of data, among other issues, determines the choice of elasticity for the measurement of the rebound effect. In case no or no suitable data are available for the computation of energy efficiency elasticities, the size of the rebound effect can alternatively also be estimated by means of price elasticities, using the following definitions (Sorrell and Dimitropoulos, 2007: 8-12):

$\eta_{P_S}(S)$: Elasticity of demand for useful energy (*S*) with regard to the cost of useful energy/work (P_S)

$\eta_{P_E}(S)$: Elasticity of demand for useful energy with regard to energy price (P_E)

$\eta_{P_E}(E)$: Elasticity of energy demand (*E*) with regard to energy price.

The negative of $\eta_{P_S}(S)$, $\eta_{P_E}(S)$ or $\eta_{P_E}(E)$ can under certain assumptions approximate $\eta_\varepsilon(S)$ and thus allow to determine the rebound effect. Equation (5) defines the rebound effect by means of the elasticity $\eta_{P_S}(S)$ (Sorrell and Dimitropoulos, 2007: 8-12):

$$\eta_\varepsilon(E) = -\eta_{P_S}(S) - 1. \tag{5}$$

In many cases there are no data about energy efficiency data available, or they are not usable. The elasticities $\eta_{P_E}(S)$ and $\eta_{P_E}(E)$ do not require this information and define the rebound effect in equations (6) and (7) (Sorrell and Dimitropoulos, 2007: 8ff):

$$\eta_\varepsilon(E) = -\eta_{P_E}(S) - 1 \tag{6}$$

$$\eta_\varepsilon(E) = -\eta_{P_E}(E) - 1. \tag{7}$$

Note that the calculation of the rebound effect by means of these two elasticities is only valid if two assumptions apply. First, consumers have to react to a price decrease in the same way as to an increase in energy efficiency (and vice versa). Second, energy efficiency must not be influenced by changes in energy price ($\eta_{P_E}(\varepsilon)=0$) (Sorrell and Dimitropoulos, 2007: 10).

Note that the definition of the rebound effect by means of $\eta_{P_E}(E)$ from (7) is particularly useful, if energy demand is attributable to a single energy service (e.g. space heating). In contrast, if demand is derived from a bundle of energy services, such as for instance electricity consumption of a household, the price elasticitiy is less useful as a rebound measure (Sorrell and Dimitropoulos, 2007: 10).

There is a possibility that the computation by means of equation (7) overestimates the rebound effect. This overestimation can be attributed to the following reasons (Sorrell and Dimitropoulos, 2007: 12): (i) correlation between energy efficiency and other input factors; (ii) endogeneity of energy efficiency; and (iii) role of time costs and energy efficiency in the production and consumption of energy services.

Regarding (i), capital costs are especially relevant in the context of correlation with energy efficiency. For instance, the price of a new central heating rises the more energy-efficient it is. We can assume that increased capital costs decrease the demand for useful energy in the long run. If this reduction in demand is lacking in the calculation of the rebound effect, the result can be upward biased (Sorrell and Dimitropoulos, 2007: 13).

Regarding (ii), the definitions of the rebound effect in (4)–(7) assume that the energy efficiency is exogenously given. In reality, energy efficiency may be influenced by one or more variables. In particular, energy efficiency can be a function of energy price. In the short run, increased energy prices can be expected to lead to energy-saving behavior of energy consumers. In the long run, consumers could opt for the adoption of more energy-efficient products (Sorrell and Dimitropoulos, 2007: 15f).

On the basis of assumptions on endogenous energy efficiency, (8) yields an expression on the relative size of the respective price elasticities (Sorrell and Dimitropoulos, 2007: 16).

$$\left|\eta_{P_E}(S)\right| \leq \left|\eta_{P_S}(S)\right| \leq \left|\eta_{P_E}(E)\right| \leq \left|\eta_{P_S}(E)\right|. \qquad (8)$$

This expression shows that for a particular energy application the elasticitiy $\eta_{P_E}(E)$ constitutes an upper bound for the rebound effect (Sorrell and Dimitropoulos, 2007: 16)

Regarding (iii), Binswanger (2001) argues that time cost and time efficiency have an important impact on the energy use and especially on the rebound effect. Some energy applications allow for a trade-off between time and energy efficiency. For instance, a sports car is less energy-efficient as a compact car, but may save some time. If such a trade-off is possible in the case of an energy application, for certain assumptions the rebound effect may be overestimated. The relative significance of time costs and energy costs, however, can vary over time and also among the various energy applications. In the case of heating of residential households, we can assume that time costs have a lesser impact on the demand for energy appliances (Sorrell and Dimitropoulos, 2007: 19f).

3.3 Application to residential heating

The discussion in the previous sections can be transferred to the determination of the rebound effects for space heating in German households. In principle, the size of the rebound could be determined by the elasticity of energy demand with regard to the energy efficiency ($\eta_{\varepsilon}(E)$). For the specific case space heating, for example, indoor room temperature can be used for the measurement of useful work. The energy system required, in the form of heating pipes, insulation, etc., for the conversion of energy forms and the supply of space heating has an individual energy efficiency. The measurement of the energy efficiency can then be made, for example, in terms of indoor room temperature per kWh of energy. By improving energy efficiency the costs of space heating of a household decrease. Through the cost advantage it is possible that the households, as a consequence, consume more space heating by choosing a higher indoor room temperature or by heating more rooms. The resulting rebound effect can then be measured by the elasticity of energy efficiency.

Since the dataset available to us does not include information on energy efficiency and useful energy, we had to use the elasticity of energy demand with regard to energy price ($\eta_{P_E}(E)$) in order to estimate the rebound of space heating in German households. Note that this measure has the important advantage in statistical inference of featuring a much higher variation than energy efficiency.

In the following section, we describe the necessary econometric approach and report on the results obtained for the level of the rebound effect.

4. The Model

In order to estimate the size of the rebound effect we describe energy consumption of the households for heating by

$$\ln(q_{it}) = \beta_0 + \beta_{p_e} \cdot \ln(p_{eit}) + \beta_x \cdot x_{it} + \alpha_i + u_{it}\,. \qquad (9)$$

This model allows for a regression of the log of the annual residential energy consumption for heating, $\ln(q)$, on the log of real energy price, $\ln(p_e)$. The coefficient is the elasticity of energy demand with respect to energy price and, according to (9), can be used for computing the rebound effect. Due to the double-logarithmic functional form, the elasticity can be identified directly from the results. Furthermore, we introduce additional independent variables, which are represented by vector x_{it} in (9). The variables of the model are described in detail in section 5 (and summarized in Table 1).

Index *i* denotes the individual household and *t* the time period concerned. Unobservable effects, which are individual and time-constant, are expressed by variable α_i. Time-dependent characteristics of the individual households are given by the idiosyncratic error term u_{it}. The variable α_i and the idiosyncratic error term u_{it} together form the error term.

5. The Data

For our analysis we have used data of the German Socio-Economic Panel (SOEP) provided by the German Economic Research Institute / DIW Berlin (Wagner et al., 2008). The SOEP is a representative repeated survey among approximately 11,000 households in Germany, initiated in 1994. It offers annual microdata for the measurement of biographical developments for basic research and policy advice in the social, economic, and behavioral sciences; it is both a household panel as well as a cohort study (Wagner et al., 2008: 301). The target population for the survey is the German population, and the goal of the panel study is the gathering of representative microdata of persons, households and families, in order to measure persistence and changes in living conditions (Haisken-DeNew and Frick, 2005: 16).

The survey is conducted by drawing a random sample among all households, in which all household occupants become survey units. Once a year the households and all living persons above 17 years of age are personally interviewed. Data collection is made by questionnaires, which are filled in by the household members. Additionally, characteristics of the households are collected in a separate household questionnaire by the main interviewee of the household. The SOEP survey spectrum is divided into a core area and a changing special thematic area. The core of the survey contains questions on the following areas: (1) demographics and living conditions; (2) Personal characteristics and basic attitudes; (3) pre-school and school education, professional education and training, qualifications; (4) labor market and professional mobility; (5) income, wealth and social security; (6) health; and (7) worries and satisfaction.

The relevant SOEP data used in our study are exclusively from the household questionnaire. They comprise, among others, data on the year of construction of the residential dwelling, the size of the dwelling (measured in m^2 and number of rooms) as well as the total monthly disposable income of all household occupants. Furthermore, the households have to indicate the installation of new windows and central and floor heating since the beginning of the previous year of the survey. The questionnaire also contains items on costs of living/dwelling. Owners and tenants provide separate data on the level of the heating costs. Specifically, owners are asked about the heating costs of the last calendar year, while tenants provide data on the average monthly heating costs (to be estimated if not know exactly). Also, the number of occupants is being gathered. For unique identification each participating household is assigned a household identification number (SOEP, 2009). All monetary data in the household questionnaire since 2002 are given in Euros, while before that they were expressed in Deutschmarks. The variables disposable income and heating costs were converted from DM to Euro from 1999 to 2001 by using an exchange rate of 1.95583.

The SOEP survey is aimed at continuity. If an occupant of a household moves, the person remains in the database, but is henceforth listed as a separate 'household'. Likewise, sample participants not originally present in a household are included in the survey. For a more detailed description and overview of the SOEP panel see Goebel et al. (2008) and the SOEP desktop companion (Frick and Haisken-DeNew, 2005).

For our analysis, we have expanded the SOEP data with further, publicly available data, and also added an additional, self-constructed variable. As additional data, we have included heating degree days[2], accounting for climatic heterogeneity of residential households. Energy consumption (in logs), the dependent variable in our models, is a computed variable that is added to the SOEP data set. It was constructed on the household level from the heating costs and the weighted average of fuel costs. If heating costs (in € per annum) are divided by the fuel price (€ per kWh), we obtain the energy consumption per household expressed in kWh per year. The fuel price is composed of the prices for different fuels used in German households, including light heating oil, natural gas, electricity, lignite briquettes, and district heating (BMWi, 2009). Prices are weighted according to the 2006 percentage shares of dwelling units with a particular type of energy source for heating (2006: 48.6% natural gas, 30.2% oil, 13.2% district heating; 4% electricity, 3% renewables, and 1% briquettes). The

[2] Heating degree days (HDD) are counted if the outside temperature is below a certain threshold value. According to VDI-Richtlinie 2067/DIN 4108 T6, the threshold value is 15 °C (cf. Recknagel et al., 2007: 14f).

weights were first surveyed in 1998 and since then updated every four years (Statistical Office, 2006; 2008: 292).

The SOEP data set for a particular year was extended by the fuel prices and the heating degree days of the previous year. This is so because the SOEP data are collected at the beginning of each year (Göbel et al., 2008: 311). In other words, the SOEP survey is not done on a single day but the field work is conducted in the first quarter of each year. Even more so, some data required for our econometric modeling are actually from the previous year (see above). Other variables remain constant, i.e. they do not change compared to the previous year (e.g. dwelling space does not change relatively to the previous year if the information is collected for the current year).

Fuel prices, heating cost and disposable income are used in real terms (base year 2007, data from Statistical Office, 2009).

The data used in our study are for the period 1999–2007. The panel data on the household characteristics considered in our modelling are unbalanced. The size of the survey is 113,662 samples.

Table 1: Definition of variables and descriptive statistics

Variable definition	**Unit**	**Variable name**	**Mean**	**SD**
Energy consumption, owner (in logs)	kWh	$\ln q_O$	9.83	0.55
Energy consumption, tenant (in logs)	kWh	$\ln q_T$	9.59	0.52
Energy price, real (in logs)	€/kWh	$\ln p_E$	-2.91	0.14
Living space	m²	LivingSpace	97.83	45.50
Household real disp. income (in logs)	€	$\ln y$	7.67	0.59
Heating degree days	°K days/ year	HDD	3036.60	124.60
Occupants per household	-	HouseholdSize	2.36	1.27
Year of construction of building	-	ConstructionYear	3.45	1.66
Dummy: 1 if new windows installed since previous year	-	Window	0.04	0.20
Dummy: 1 if new heating system installed since previous year	-	Heating	0.02	0.15

The results of the test for heterogeneity for owners and tenants are given in Table 2. The test results show that for the data sample used there is indeed unobserved heterogeneity. The result of the Hausman Test shows that the group-specific error terms correlate with the central independent variable, so that we ought to apply a *fixed effects* model (Cameron and Trivedi, 2005: 717f). The result of the Hausman Test for tenants yields the same conclusion, i.e. again a *fixed effects* model is preferred to a *random effects* model. Table 2 also depicts the test results for autocorrelation and heteroscedasticity both for building owners and tenants. Again, we find autocorrelation and heteroscedasticity, so that standard errors need to be adjusted accordingly in order to use them for significance testing (Yaffee, 2003), which we have done.

A test of the dependent variables by symmetry plots shows for the energy consumption of the tenants, $\ln(q_T)$, as well as for the homeowners, $\ln(q_O)$, an asymmetric relationship (see the Appendix). The presence of groupwise heteroscedasticity in the case of fixed effects can be confirmed by means of a modified Wald Test (Greene, 2000: 598).

The results of the heterogeneity and autocorrelation tests for homeowners are shown in the second column of Table 2. The results confirm the existence of autocorrelation in the data and reveal the violation of the homoscedasticity assumption, and the need to properly address the issue of heteroscedasticity in the model estimation.

Table 2. Diagnostic tests

Test statistic	**Owners**		**Tenants**	
Breusch-Pagan ML test for unobserved heterogeneity	$\chi^2(1) = 1294.05$	Prob > χ^2 = 0.0000	χ^2 (1) = 688.66	Prob > χ^2 = 0.0000
Hausman test for choice between fixed vs. random effects model	χ^2 (8) = 164.81	Prob > χ^2 = 0.0000	χ^2 (8) = 23.52	Prob > χ^2 = 0.0028
Modified Wald test for heteroscedasticity	χ^2 (5246) = 2.9e+34	Prob > χ^2 = 0.0000	χ^2 (4586) = 6.4e+33	Prob > χ^2 = 0.0000
Wooldridge test for autocorrelation	F (1, 4882) = 93.569	Prob > F = 0.0000	F (1, 3106) = 36.664	Prob > F = 0.0000

6. Results

For the econometric estimation, we have made use of the Stata software, Version 8 (Stata Corp., 2003). The model coefficients were estimated with two procedures, *areg* and *xtivreg2*.[3] The procedure *areg* enables the estimation of a fixed effects model. In order to obtain robust standard errors regarding the autocorrelation and heteroscedasticity present, we used the ID number of the households for clustering. The procedure *xtivreg2* is an ado-file from the Statistical Components Archive (www.repec.org). In contrast to *areg*, the *xtivreg2* procedure does not rely on clustering, but instead it produces Newey-West standard errors (Newey and West, 1987).

6.1 Owners

For the estimation of the fixed effects model and all income classes we had 7328 observations when using the *xtivreg2* procedure, and 9461 observations using the *areg* procedure. We find a rebound effect for home owners of 12.2% and, on the basis of an *F*-test, that despite a number of insignificant coefficient estimates for the control variables (except for *HDD* and *HouseholdSize*) both model variants are significant. The estimate obtained for the energy price coefficient is slightly more significant for the *xtivreg2* procedure (i.e. at the 1% level) than for the *areg* procedure (5% level). The signs of the insignificant coefficients are all intuitive except for the disposable income.

Next, we turn to the results for the lower income households (i.e. disposable income < €2710 per month). This time, the *F*-test rejects the *areg* model variant, while the *xtivreg2* model specification is significant at the 10% level. The energy price coefficient suggests a rebound effect of 13.4% for owners of the low income class. Similarly to the estimates for the entire owner sample, most coefficients of the control variables are statistically not significant. The signs of all coefficients, except of the one for the dummy variable *Window*, are intuitive. Finally, for the higher income households (disposable income > €2710) we make use of 4959 (3476) observations for the *areg* (*xtivreg2*) procedure. In this case, the rebound effect is shown to amount to some 13.6%. As before, most coefficient estimates are insignificant,

[3] The *areg* procedure fits a linear regression absorbing one categorical factor. It suppresses the values of the coefficients for each dummy variable while automatically calculating and displaying the test of their joint significance. *xtivreg2*, in contrast, implements IV/GMM estimation of fixed effects and first-differences panel data models with possibly endogenous regressors.

except for the *HDD* variable (1% level, both variants) and *HouseholdSize* (5% level, *xtivreg2* variant only).

6.2 Tenants

Analogously to the estimation for owners, we estimated a fixed effects model for the tenant households. If the two income classes are put together to one sample, we have 7463 observations (*areg*) and 5117 observations (*xtivreg2*), respectively. This time the estimate of the energy price coefficient suggests a loss in potential energy savings, and thus a rebound effect, of almost 40%. Regarding the control variables, except for *LivingSpace* all of them are insignificant. As for the case of home owners, the signs of the coefficients for *LivingSpace*, *HDD* and *HouseholdSize* are the expected ones. This time, however, also the coefficient for the income variable has the expected sign, whereas in contrast to the results for the owner households, *ConstructionYear*, *Window* and *Heating* do not. Again, the model specifications are highly significant (1% level) for both model variants (see Table 4, bottom).

If only the low income tenant households are considered, the regression analysis comprises households having a monthly net income of less than €1920. In this case, the data set used for the estimation contains 3790 observations for model variant *areg* and 2179 observations for *xtivreg2*. As Table 4 shows, for low-income households the energy price coefficient suggests a rebound effect of about 49.3%. In other words, the results indicate that almost half of the energy savings potential is lost to behavioural adjustment. The result for the energy price coefficient as a measure of the direct rebound effect is for both model variants significant at the 1% level. This time, the coefficients of the control variables all have an intuitive sign, but are statistically insignificant except for *LivingSpace* (significant at the 5% level for the *xtivreg2* model variant). Even though most coefficients are insignificant, the *F*-tests for the entire model are significant for both model variants (see bottom of Table 4).

Finally, we turn to the high income class (> €1920 per month) of the tenant households (*xtivreg2*: 2253 obs., *areg*: 3673 obs.). This time, obtain a rebound effect of 31.4%, and thus the lowest rebound estimate for the tenant households. Apart from the energy price coefficient, only the *LivingSpace* coefficient is significant (*xtivreg2*: 1%, *areg*: 5%). Note that in contrast to the previous results, however, not all coefficients of the control variables show the expected signs. Last but not least, according to the *F*-tests, both model variants are significant at the 5% level, the *xtivreg2* variant even at the 1% level.

Table 3. Fixed effects model estimates, owners

Income class	**All**				**Low (≤ € 2710)**				**High (> € 2710)**			
Model variant	*areg*		*xtivreg2*		*areg*		*xtivreg2*		*areg*		*xtivreg2*	
Dep. var.: ln q_E	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE
ln p_E	-0.1221**	0.0634	-0.1221***	0.0452	-0.1335	0.1121	-0.1335*	0.0750	-0.1355	0.0891	-0.1355**	0.0596
LivingSpace	0.0005	0.0011	0.0005	0.0008	0.0023	0.0013	0.0023***	0.0008	0.0009	0.0008	0.0009	0.0005
ln y	-0.0400	0.0685	-0.0400	0.0512	0.0257	0.0785	0.0257	0.0545	-0.0328	0.0718	-0.0328	0.0480
HDD	0.0004***	0.0001	0.0004***	0.0001	0.0002	0.0002	0.0002**	0.0001	0.0005***	0.0001	0.0005***	0.0001
HouseholdSize	0.0576**	0.0279	0.0576***	0.0197	0.0317	0.0592	0.0317	0.0370	0.0488	0.0367	0.0488**	0.0233
ConstructionYear	-0.0143	0.0278	-0.0143	0.0213	-0.0134	0.0406	-0.0134	0.0296	-0.0352	0.0306	-0.0352	0.0246
Window	-0.0012	0.0460	-0.0012	0.0332	0.0220	0.0724	0.0220	0.0477	0.0302	0.0567	0.0302	0.0386
Heating	-0.0704	0.0720	-0.0704	0.0523	-0.0266	0.1102	-0.0266	0.0735	-0.0246	0.0642	-0.0246	0.0428
Constant	8.4375***	0.6639	-	-	8.2558	0.8795	-	-	8.0498***	0.7454	-	-
F-tests for model significance:												
	F(8, 5245) = 4.09		F(8, 4207) = 7.06		F(8, 2790) = 0.79		F(8, 1703) = 1.70		F(8, 2968) = 3.47		F(8, 1982) = 6.56	
	Prob > F = 0.0001		Prob > F = 0.0000		Prob > F = 0.6138		Prob > F = 0.0926		Prob > F = 0.0005		Prob > F = 0.0000	

Note: * significant on the 10% level; ** significant on the 5% level, *** significant on the 1% level;

Table 4. Fixed effects model estimates, tenants

Income class	**All**				**Low (≤ € 1920)**				**High (> € 1920)**			
Model variant	*areg*		*xtivreg2*		*areg*		*xtivreg2*		*areg*		*xtivreg2*	
Dep. var.: ln q_T	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE
ln p_E	-0.3998***	0.0802	-0.3998***	0.0525	-0.4933***	0.1425	-0.4933***	0.0852	-0.3136***	0.1261	-0.3136***	0.0773
LivingSpace	0.0054***	0.0015	0.0054***	0.0010	0.0055	0.0038	0.0055**	0.0023	0.0050**	0.0023	0.0050***	0.0014
ln y	0.0250	0.0509	0.0250	0.0337	0.0354	0.1087	0.0354	0.0661	-0.0450	0.1087	-0.0450	0.0656
HDD	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0001	0.0001	0.0002	0.0001	0.0001
HouseholdSize	0.0230	0.0347	0.0230	0.0221	0.0326	0.0868	0.0326	0.0493	0.0391	0.0497	0.0391	0.0298
ConstructionYear	0.0073	0.0233	0.0073	0.0158	-0.0125	0.0335	-0.0125	0.0213	0.0085	0.0411	0.0085	0.0262
Window	0.0136	0.0778	0.0136	0.0514	-0.0080	0.1255	-0.0080	0.0801	0.0208	0.1476	0.0208	0.0887
Heating	0.0091	0.1030	0.0091	0.0655	-0.1453	0.1861	-0.1453	0.1092	0.1108	0.1587	0.1108	0.0940
Constant	7.3867***	0.5833	-	-	6.9499***	1.0411	-	-	8.3417***	1.1407	-	-
F-tests for model significance:												
	F(8, 4585) = 5.81		F(8, 2869) = 13.21		F(8, 2596) = 2.34		F(8, 1185) = 6.17		F(8, 2412) = 2.02		F(8, 1252) = 5.22	
	Prob > F = 0.0000		Prob > F = 0.0000		Prob > F = 0.0168		Prob > F = 0.0000		Prob > F = 0.0404		Prob > F = 0.0000	

Note: ** significant on the 5% level, *** significant on the 1% level

6.3 Comparison of results and discussion

Table 5. Summary table of the estimation results for the rebound effect

Income class	**Rebound effect, owners [in %]****	**Rebound effect, tenants [in %]****
All	12	40
Low	13	49
High	14	31
Average*	13.5	40

Note: * Average between low and high income class, ** estimates rounded

The comparison across all income classes shows that the rebound effect is much larger for tenants than for owners. With an effect of 40% only 60% of the potential energy savings of tenants are realized, whereas owners seem to realize 88% of the energy savings potential.

Recalling the reasons given for overestimating the rebound effect in section 3.2 (i.e. correlation between energy efficiency and other input factors; endogeneity of energy efficiency; and the role of time costs and energy efficiency in the production and consumption of energy services), we expect an upward bias of the estimates for owners. The expectation of an upward bias, however, does apply less so for tenants, since they do not invest as heavily in energy-saving equipment as owners.

The expectation of a higher rebound effect for low income class households is fulfilled for tenants. Households with low income reduce the energy savings potential by about half. High income households feature a rebound effect of 31%. However, the saturation effect apparently does not play a role for owners. The rebound effect for both high and low income households in this case is only one percentage point apart (13% vs. 14%).

The lower average income of tenants could be a possible cause for the occurrence of saturation effects for only this group of households. As Milne and Boardman stated, the rebound effect in low-income strata can be expected to be larger, since room temperature is often further away from the most comfortable living temperature (Milne and Boardman, 2000: 422). Conversely, the more the indoor temperature is aligned to the most comfortable living temperature, the lower the rebound effect can be expected to be (Sorrell et al., 2009: 1357).

The results from our study, and those reported of others in section 2, are quite similar in their magnitude. In all studies, the existence of a rebound effect could be shown. Without differentiation by income class the rebound effects estimated in our study range from 12-40%. The rebound effects from the other studies cited vary, on average, between 21-43%. Guertin et al. (2003: 34) obtain different results when income classes are differentiated. Specifically, households from high income class exhibit a rebound of 34%. The rebound in the low income class is at 51%. The results for tenants in our study range from 31% for low income to 49% for high income households. In both studies differences in the size of the rebound effect by income differentiation could be detected. Although the studies, due to different framework conditions, are not strictly comparable, all results obtained point in the same direction. The direct rebound effect exists for space heating in private households and is significant in size.

The results from our study, according to (8), are an upper bound for the actual rebound effect. From the equation we can see the delimitation of the elasticity used $\eta_{P_E}(E)$ to the other rebound definitions. Applying other definitions, and including some information on energy efficiency (if available), could lead to lower rebound estimates.

7. Summary and conclusions

Climate change mitigation requires a reduction in energy consumption and CO_2 in all sectors of the economy. To tackle this challenge also rigorous energy efficiency measures are needed. The implementation of these measures requires financial incentives and a solid regulatory framework provided by government. On the level of building technology, the European Commission has implemented a Directive in 2002 concerning total energy efficiency of buildings, which has to be implemented by the member states into national legislation. In Germany, a revised Energy Saving Ordinance has entered into force in 2009.

In Germany, space heating accounts for about one third of total energy consumption and is thus a major share. The single-largest share of energy consumption of residential households is the one for space heating. Existing buildings have a substantial energy savings potential. The aim of the German Energy Savings Ordinance (EnEV, 2009) is to exploit the energy savings potentials and to fulfil the obligations under the relevant EU directive (CEC, 2002). As heating of residential buildings in Germany is still largely based on fossil fuels, despite the diffusion of new types of heating systems (heat pumps, wood pellet; cf. Michelsen and Madlener, 2011), a reduction in energy consumption is an effective way to reducing CO_2 emissions.

After the introduction of an energy efficiency measure a change in energy consumer behavior of the private households can reduce the expected energy savings potential based on engineering-economic calculations. This effect is known as "rebound effect" and can even lead to an increase in energy consumption as a consequence of energy efficiency improvements (“backfiring”).

In this study, based on panel data, we investigated the size of the rebound rebound effect for space heating in German residential households and thus its relevance for energy and environmental policy-making. To this end, we have briefly described the various types of rebound effects, rebound definitions, and some empirical literature on the rebound effect concerning space heating. Also, we have shown that comparable studies on other countries range from 21% to 43%. In our analysis, we have defined the (direct) rebound effect by energy price elasticities, and discussed several reasons for possible over-estimation of the effect.

Based on the theoretical considerations, we then developed an econometric model. By means of a *fixed effects model*, we estimated the rebound effect based on separate data sets for owners and tenants, which were additionally split by income group (all, low, high). The definition by elasticity of energy demand with respect to energy price allowed us to estimate the size of the rebound effect from the models. The existence of a rebound effect could be confirmed for each group of households considered. The results for all income classes together range from 12% for owners to 40% for tenants. The rebound effect for tenants in the low income class (49%) was the highest estimated. We suspect that the results for the household owners could be upward biased.

Although energy efficiency improvements can provide economic gains to households, the effectiveness of a reduction in energy demand and the related environmental burden depends on behavioral change. Energy efficiency improvements, *ceteris paribus*, induce a reduction in the cost of the energy service concerned. The more energy households demand due to these price reductions, the lower are the improvements to be reaped in terms of environmental impact and energy dependence. The results of our study suggest that only between 51% and 88% of the energy saving potentials in the German residential sector have actually been realized.

Compared to other studies our results are quite similar. We can learn that potentials for climate change mitigation do not only depend on the technical measures adopted, but also very much on behavioral change due to efficiency gains. On the one hand, energy efficiency measures do have the potential to reduce energy consumption, but on the other hand can be disputed in terms of their effectiveness due to the rebound effect.

Overall, the results indicate that political measures for reaping the benefits from energy efficiency improvements, unless coupled with rebound-reducing measures (cap-and-trade, information campaigns etc.), may contribute only to a limited extent to the reduction in energy demand. On the basis of our results it becomes evident that the prevailing political measures need to be refined, adapted, and extended. In particular, after the Climate Conference in Copenhagen, the existence of the rebound effect should be moved into the consciousness of the people and induce energy policy measures that adequately take into account the behavior of energy consumers, and that discriminate by ownership and disposable income of households.

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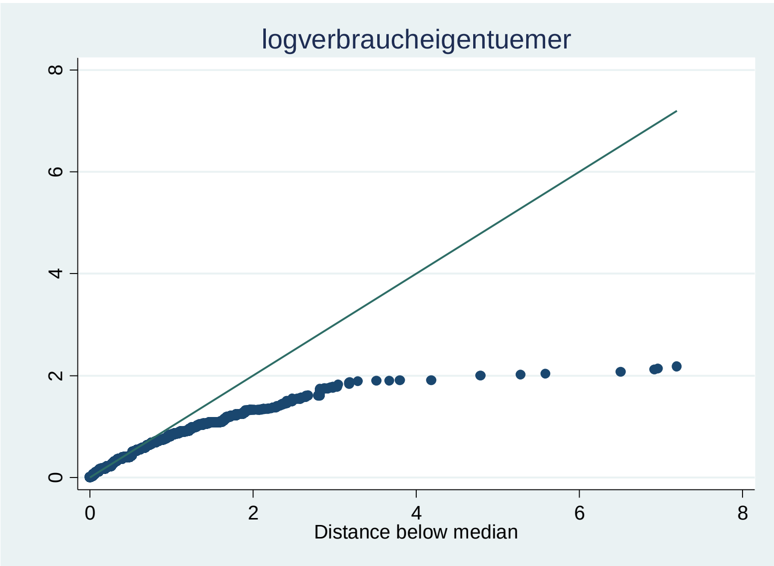
Appendix

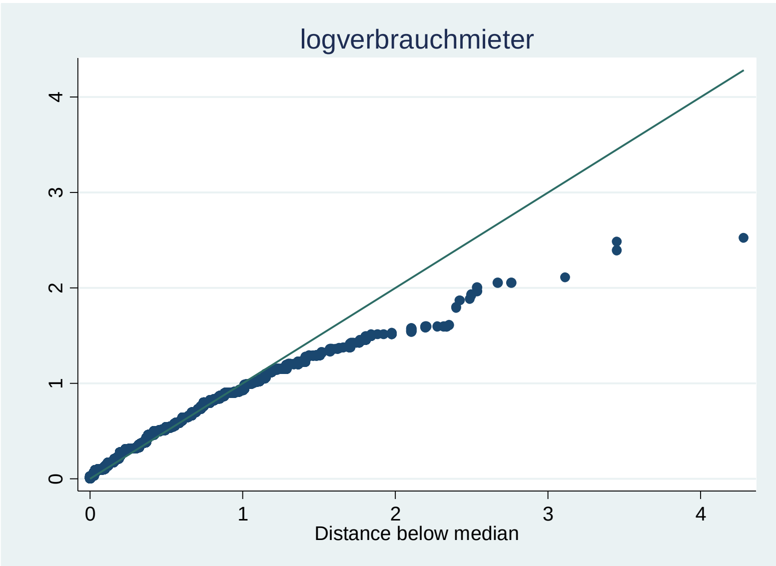
A.1 Homoscedasticity

A test for heteroscedasticity of the dependent variables for owners (plot a) and tenants (plot b) is depicted in Figure A.1, allowing for a visual inspection of the distribution. The symmetry plots measure the distance above the median for the *i*th value against the distance below the median for the *i*th value. As can be seen both distributions are highly non-symmetric, the owner symmetry plot even more so than the one for the tenants.

Figure A.1: Symmetry plots energy consumption



(a) Owners



(b) Tenants

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