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Does subsidizing investments in energy efficiency reduce energy consumption? Evidence from Germany

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Abstract

Improving energy efficiency is one of the three pillars of the European energy and climate targets for 2020 and has led to the introduction of several policy measures to promote energy efficiency. The paper analyzes the effectiveness of subsidies in increasing energy efficiency in residential dwellings. An empirical analysis is conducted in which the effectiveness of subsidies on the number of dwelling modernizations is investigated. Next, the impact of renovations on energy consumption is analyzed using a differences-in-differences-in-differences approach for modernizations made in given subsidy program periods, as well as for ownership status and household types for more than 5000 German households between 1992 and 2010. By controlling for socio-economic status, dwelling characteristics and macro-indicators, it becomes apparent that homeowners invest significantly more and have significantly lower heating expenditures than their tenant counterparts. Thus, the landlord-tenant problem tends to broaden the energy efficiency gap. It is also found that the number of modernizations made by landlords does not increase with higher subsidies. However, the renovations made during the subsidy periods decrease the heating consumption of tenants. Given the conditions that homeowners already invest more in energy efficiency, they increase modernizations only slightly with increasing subsides. However, these modernizations during subsidy periods do not further decrease homeowners' energy consumption. Thus, the large part of the overall subsidies received by homeowners can be identified as windfall profits.

Keywords: Household behavior, econometric analysis, energy efficiency, demand modelling

JEL classification: D12, Q51, R21

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1. Introduction and Background

The promotion of energy efficiency in the residential sector has already been addressed in public policies for several decades. Reasons for the attention have been diverse. High prices of heating energy during the oil crises, fossil fuel depletion and the reduction of greenhouse gas emissions following the UNCED[1] in Rio de Janeiro 1992 are common explanations. More recently, the Stern Review (Stern, 2007) and the IPCC reports on climate change in 2001 and 2007 (IPCC, 2001, 2007) have increased awareness. In the current European political debate, the curtailment of energy consumption, especially of fossil fuels, and the abatement of greenhouse gas emissions are major objectives of European energy policy. The EU is aiming to cut 20% of Europe's annual primary energy consumption by 2020 (European Commission, 2011).

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[1]United Nations Conference on Environment and Development

The European Commission estimated buildings to cause 40% of final energy consumption and 36% of greenhouse gas emissions in the European Union, mainly caused by space and water heating (European Commission, 2012). Major energy savings can only be achieved by increasing energy efficiency, requiring significant investments. Improvements of the level of energy efficiency of buildings, such as improvements in heat insulation, imply high initial investment costs for households. These high investment costs are associated with three major obstacles for reaching the policy objectives of energy savings in residential dwellings. First, households may underinvest causing the cost-minimizing level of investment in energy efficiency to deviate from realized investments, often referred to as the 'energy efficiency gap'(Allcott and Greenstone, 2012). These underinvestments may be a result of hyperbolic discounting, major credit constraints or specific information asymmetries. Second, inefficiently high energy consumption may occur, despite investments in energy efficiency, referred to as the rebound effect. Third, the principal-agent problem between landlords and tenants reduces incentives to invest in energy efficiency improvements. This so-called landlord-tenant problem (Jaffe and Stavins, 1994) characterizes barriers for landlords to ensure appropriate investment returns by including investment costs in the rent.

Therefore, an evaluation of policy measures to enhance energy efficiency in residential dwellings should consider both the impacts on investments and on energy consumption. Subsidies being prominent policy measures may give incentives for investments in energy efficiency, e.g. by reducing credit constraints, which may result in a larger number of renovations (quantity effect). In addition, or alternatively, subsidies may increase the degree of energy efficiency that is achieved through the subsidized investments (quality effect). Hence, the comprehensive research question may be raised whether subsidies have such a quantity and/or quality effect. The presented paper attempts to analyze both effects by performing a twofold analysis to investigate how subsidies can promote investments in energy efficiency and reduce energy consumption. Moreover, specific attention should be given to the landlord-tenant problem when considering residential dwellings. Thus, the paper raises further questions of how the landlord-tenant problem affects heating energy consumption and how the policy measures work given different owner and landlord investment and owner and tenant energy consumption behavior.

Germany is an important subject to consider since Germany has highly ambitious national objectives concerning greenhouse gas reductions and improvements in energy efficiency. Germany set a target of 40% reduction and voluntarily aims at outperforming the EU targets of 20% greenhouse gas abatement until 2020 relative to the levels of 1990 (The Federal Environment Agency (Umweltbundesamt), 2007). In fact, the German government spent more than 6.5 billion Euros between 1996 and 2002 and an additional 31.5 billion Euros between 2003 and 2010 to promote investments in energy efficiency in residential dwellings in Western Germany (KfW (Kreditanstalt für Wiederaufbau), 2012). Moreover, Germany has a high proportion of households that live in rented dwellings and therefore may be strongly affected by the landlord-tenant problem.[2]

Therefore, using detailed micro-data on dwelling modernizations and heating expenditures, as well as socio-economic and dwelling characteristics of more than 5000 German households for the period 1992–2010, the impact of policy measures on investments in energy efficiency and their impact on energy expenditures are investigated in the presented paper. The analysis is performed by assessing the standard policies used to increase investments in energy efficiency, i.e. lump-sum subsidies and subsidized credits. The empirical analysis proceeds in two steps. In the first step, the effects of the subsidies on the probability of dwelling modernizations are analyzed, controlling for household and dwelling characteristics. In a second step, the empirical analysis investigates the impacts of dwelling modernizations made during the periods of the subsidy program on heating expenditures. In this analysis, a differences-in-differences-in-differences approach is applied to control for the difference between owner- and tenant-occupied dwellings, the heterogeneity of households and modernization trends.

The major empirical findings of the paper show that subsidies spent on dwelling modernizations only have a slight impact on the probability of renovations, i.e. a slight quantity effect, and only in owner-occupied dwellings. However, referring to the quality effect, the investments made during the subsidy period

[2]The proportion of German households that rented is more than 50% compared to less than 30% in the United Kingdom or even less than 20% in eastern European countries (Eurostat, 2010).

only reduce energy consumption in tenant-occupied buildings excluding the effect of the generally lower energy expenditures of homeowners. In summary, the empirical results show that subsidies have only a minor quantity and no quality effect in owner-occupied dwellings and thus reveal that subsidy payments for owners are mostly windfall profits. There is no quantity effect on modernizations in tenant-occupied dwellings and quality effects are small. Moreover, the results provide evidence for the landlord-tenant problem and the lack of investments in tenant-occupied dwellings. Tenants live in significantly less insulated homes and consume more heating energy per square meter.

The next section provides a literature overview and Section 3 presents the hypotheses of the estimations. Section 4 describes the database. In addition to the socio-economic and dwelling characteristics, policy variables are included in the analysis, reflecting the subsidies spent for housing reconstructions. The estimation strategy is presented in Section 5 as well as the applied differences-in-differences-in-differences approach used to analyze the impacts of the investments made during the subsidy program periods, while controlling for homeownership. Section 6 provides evidence of the effects of policy measures and further variables on the probability of dwelling modernizations. Furthermore, Section 6 discusses the empirical results on the determinants of heating energy and warm water expenditures and the impact of investments made during the subsidy program periods in owner- and tenant-occupied dwellings. Section 7 concludes the analysis.

2. Literature overview

A broad range of literature analyzes the determinants of energy consumption: Baker et al. (1989) investigate the determinants of electricity and gas demand for households during the period 1972 to 1983, accounting for socio-economic characteristics such as ownership, household size and income, as well as details of the dwelling such as the number of rooms. They find that energy consumption increases with income and that the price sensitivity of households is higher for families with children and lower income. Meier and Rehdanz (2010) investigate determinants of residential space heating expenditures in the UK in a panel data analysis of more than 5000 households for the years 1991 to 2005. They analyze socio-economic factors, building characteristics, heating technologies and weather conditions, and derive price and income elasticities both for different types of British households and for Britain as a whole. They find that owner-occupied and tenant-occupied households react differently to changes in income and prices. Brounen et al. (2012) investigate the impact of dwelling and socio-demographic household characteristics on residential energy use in a cross-sectional estimation. The study shows that residential gas consumption is mostly determined by structural dwelling characteristics, such as the vintage class, building type and characteristics of the dwelling. They evaluate that well-insulated homes may reduce natural gas consumption, primarily for heating, by 12%.

Several studies have identified the need and obstacles for energy efficiency policies caused by underinvestment, the rebound effect and the landlord-tenant problem. Allcott and Greenstone (2012) present an overview of reasons for underinvestment in energy efficiency measures, often referred to as the 'energy efficiency gap' and provide a survey on the relevant literature. They identify two major market failures that need to be addressed by energy efficiency policies: the internalization of environmental externalities (such as greenhouse gas emissions) and the mitigation of investment inefficiencies. Similarly, Train (1985) shows that consumers may base their investment decisions on excessive discount rates and undervalue future benefits from energy savings.

Subsequent to dwelling modernizations as a result of lower expenditures for energy, households may increase their consumption, resulting in the so-called 'rebound effect' and counteracting energy conservation objectives. Greening et al. (2000) present different studies which analyze the rebound effect and find different magnitudes of the resulting behavioral response, depending on the deviating definitions and different empirical analyses. Furthermore, for energy end uses, they conclude that the range of estimates for the size of the rebound effect is low to moderate. Allcott (2011) shows that providing information to consumers about their energy consumption and the consumption of similar households gives an incentive to reduce energy consumption.

The landlord-tenant problem, i.e. that the investor is not the person who pays the energy expenditures, may limit investments in energy efficiency (see Jaffe and Stavins (1994)). With a low ownership rate, the German housing market is an interesting case. Regarding the impact of ownership status, Gebhardt

(2012) empirically evaluates whether the allocation of asset ownership (with the risk of expropriation) effects relationship-specific investments. In an empirical analysis of the German housing market, he finds evidence of more frequent relationship-specific investments, such as bathroom renovations, if the occupant is protected against expropriation, which is the case for homeowners. Gebhardt (2012) concludes that renovations are significantly dependent on the ownership status and his model predicts underinvestment in rental housing. Hence, the heating energy consumption of households that own their dwelling may deviate significantly from that of tenants. Rehdanz (2007) also reveals differences in owner- and tenant-occupied dwellings. She examines the determinants of household expenditures on heating and warm water supply in Germany. She includes a variety of socio-economic and dwelling characteristics in her analysis. In addition, Rehdanz (2007) finds a significant difference between the effects of energy price increases for owners and tenants, and concludes that owners are more likely to have installed energy-efficient heating and hot water supply systems.

While the aforementioned studies have identified the need for policy interventions to promote energy savings, several other papers have gone further and analyzed the impact of policy measures on energy conservation. Hassett and Metcalf (1995) investigate the effects of energy tax credits on residential energy conservation, controlling for unobserved heterogeneity of energy saving tastes. They analyze panel data on individual tax returns for residential conservation investments to measure the impact of tax policies on the probability of making these investments. They find that a 10 percentage point decrease in the tax paid on investment in energy efficiency would lead to a 24% increase in the probability of investments. Eichholtz et al. (2010) show that 'green ratings' significantly increase rents and selling prices of office buildings. Eichholtz et al. (2012) however show that this only holds among green buildings. Brounen and Kok (2011) find that consumers capitalize on information collected from energy performance certificates in the housing market and take it into account when considering the price of their prospective home. They also show that adoption rates of energy labels implemented by the European Union are low and that European policy needs to further stimulate their dissemination. Allcott and Mullainathan (2010) reason that understanding the behavior of households is crucial for the design of effective policies to reduce energy consumption. They argue that policies need to consider insights from the behavioral sciences rather than focusing solely on price changes (e.g., subsidies for energy-efficient goods) and information disclosure (e.g., through energy-use labels).

Allcott and Greenstone (2012); Allcott et al. (2012) and Heutel (2011) investigate the effectiveness of a subsidy theoretically. Allcott and Greenstone (2012) argue that if energy is priced below social cost and neither a feasible Pigovian tax nor effective information disclosure policies are available, subsidies and standards may be a second best approach. Subsidies (and standards) may cause higher welfare costs for mainly two reasons: First, subsidies change prices for all households equally despite the heterogeneity of household preferences. Second, subsidies do not price the usage of energy and may therefore rarely be targeted. Most probably, the greenhouse gas abatement level achieved by a subsidy would be higher or lower than the one achieved by a Pigovian tax. Thus, marginal abatement costs of subsidies would vary among households and would rarely equal marginal damage costs. However, Allcott and Greenstone (2012) discuss that subsidies may increase welfare by reducing credit barriers. Moreover, Allcott et al. (2012) and Heutel (2011) argue that a subsidy or standard may be optimal in addressing hyperbolic discounting or undervaluation of energy savings in contrast to a Pigouvian tax.

In summary, the majority of previous studies focus on the determinants of residential energy consumption. However, energy consumption could only significantly be reduced through investments in energy efficiency. Several studies analyze the effects of policy measures on investments in energy efficiency. The potential positive effects of subsidies on energy conservation are theoretically discussed in the literature. The presented paper contributes to the existing literature by providing evidence for the effectiveness of subsidies in an empirical analysis investigating quantity and quality effects of subsidies on investments in energy efficiency. Moreover, the impact of the landlord-tenant problem and differences between the effects of subsidies on investments in owner- and tenant-occupied dwellings have not been investigated so far. The presented paper thus attempts to fill a gap in the existing literature by empirically analyzing the different effectiveness of subsidies in owner- and tenant-occupied dwellings.

3. Hypotheses

An important instrument of the German National Energy Efficiency Action Plan (NEEAP) (Federal Ministry of Economic Affairs and Technology, 2007) to achieve the ambitious German greenhouse gas reduction targets are subsidies on investments in energy efficiency. The presented paper investigates the impact of these subsidy programs on investments in energy efficiency and on energy consumption by examining three hypotheses.

The theoretical considerations of Allcott and Greenstone (2012) and Allcott et al. (2012) have shown that subsidies may overcome credit barriers or other barriers such as hyperbolic discounting or asymmetric information problems and may increase energy conservation. Thus, the German subsidies may reduce the costs of investments in energy efficiency and hence energy consumption. These energy savings may be achieved by two effects of the subsidies. The subsidies may give incentives for more households to invest in energy efficiency, or the subsidies may increase the level of energy efficiency realized through the subsidized investments. Therefore, the following two hypotheses are evaluated:

Hypothesis 1: Subsidies may increase the number of dwelling modernizations (quantity effect).

Hypothesis 2: Subsidies may decrease energy consumption by increasing the quality of investments in energy efficiency (quality effect).

The existing literature has presented differences in investments in owner and tenant-occupied dwellings (Gebhardt, 2012) and in the energy consumption of owners and tenants (Rehdanz, 2007). Thus, the landlord-tenant problem is assumed to have significant impacts on investments in energy efficiency and thus may also have impacts on subsidized investments.

Hypothesis 3: Renovation frequency and energy consumption are different in tenant- and owner-occupied dwellings as well as the effects of subsidies.

Section 6 investigates these hypotheses in two empirical analyses.[3] The next section presents the database for these analyses.

4. Data and descriptive statistics

4.1. Sources and variables

The data used for the empirical analyses of this paper are provided by the German Socio-Economic Panel Survey (SOEP).[4] The survey is a representative and longitudinal study of private households, carried out by the German Institute for Economic Research (DIW Berlin), and includes data on household composition, occupational biographies, employment, earnings, housing, health and satisfaction indicators. The survey started in 1984 and covers nearly 11,000 households and more than 20,000 persons for each year. The data is collected by the fieldwork organization TNS Infratest Sozialforschung, which surveys the same households every year. The sample applied in this study ranges from the year 1992 to 2010 and covers more than 5000 households per year. Only data for Western Germany is used, as the structure and development of the Eastern German residential building sector is quite different than the Western German sector, especially during the first decade after the reunification. Significant amounts of money and different types of subsidies were transferred to the East after the reunification in 1990. Due to both the different types of implemented policies and the fast structural changes of the building sector in Eastern Germany, consistent impacts cannot be identified between Eastern and Western Germany. Hence, Western Germany is taken as the focus of the analysis.

[3]The hypotheses are illustrated in a simple theoretical model based on Allcott and Greenstone (2012) in Appendix B in the Appendix.

[4]Wagner et al. (2007) provide a detailed description of the panel survey.

The presented paper uses SOEP data on the household and dwelling characteristics. The economic situation of households is given in terms of disposable income and heating and warm water expenditures. Table 1 provides an overview of all variables included in the estimations. In the dataset, data on whether households made major dwelling renovations or installed new windows, which improve the state of dwelling, are covered. The two variables are combined to make the variable *dwelling modernizations*.

The variable *log. of heating expenditures per* m^2 is the logarithm of average annual heating expenditures per dwelling size. Controlling for the gas price increases, the average heating expenditure in the sample is 12.20 Euros per m^2 for an average dwelling size of 103.93 m^2 over the years 1992–2010. For owner-occupied dwellings the average heating expenditure amounts to 10.50 Euros per m^2 for an average dwelling size of 125.39 m^2. The average heating expenditure of tenant-occupied dwellings is 14.26 Euros per m^2 for an average dwelling size of 78.08 m^2.

The socio-economic (household) variables included are the logarithm of monthly disposable household income (*log. of adj. income*) and a categorial variable for different household compositions (*household type*), which increases with an increasing number of household members. A dummy variable (*owner-occupied*) indicating whether the dwelling is owner- or tenant-occupied is also included.

Variables representing dwelling characteristics used in the analyses are the *number of relocations*, i.e. how often a household relocated, the number of rooms (*room*), a categorical variable for construction periods (*construction period*), and the condition of the dwelling (*need of renovation*), which is a categorical variable from 1 to 4 with 1 indicating a good status and 4 the need for renovation. The status of the dwelling has been evaluated by the interviewed household member.

Based on the variable *dwelling modernizations*, additional variables are generated. The variable *modernized* indicates whether a household's dwelling has been modernized in previous periods. The variables *treated household group 1* and *treated household group 2* indicate the types of households that made investments during the subsidy periods 1 and 2. The subsidy period 1 indicates the years 1996–2002 and the subsidy period 2 covers the years 2003–2010.
In addition, macro-data is added, i.e. non-individual data such as heating-degree-days (*HDD*, published by Klein Tank et al. (2002)[5]) and the variable *log. of gas price*, i.e. logarithm of the annual natural gas prices index for households (published by the German Statistical Office). Only prices of gas are included as input data, since approximately 70% of all households used natural gas for heating during the time period considered and the heating systems of the single households cannot be differentiated by energy carriers. An additional 17% to 27% of all households in Germany had oil heaters.[6] As most households heat with natural gas, and as oil and gas prices are highly correlated, the gas price is assumed to be a good proxy for a heating energy price.

To cover policy impacts on the macro-level[7], annual subsidies alloted to households for dwelling modernizations (published in the subsidy reports of KfW (Kreditanstalt für Wiederaufbau) (2012)[8] are used. The subsidies are provided to households through different KfW building renovation programs primarily via direct subsidies on investment interest rates.[9]

Including these total subsidies may cause endogeneity problems. A high relative frequency of modernizations due to other reasons than the subsidies may lead to a large number of applications for a subsidy and thus increase total subsidies spent. To ascertain that causality is vice versa and to check whether increasing subsidies cause a higher probability of dwelling modernization, a subsidy ratio indicating the subsidized proportion of dwelling modernization spendings is included in the analysis. The variable *subsidy ratio* is the average subsidy divided by the average modernization expenditure in residential dwellings during a subprogram period.[10] Data on modernization expenditures of residential dwellings is provided by the German

[5]Heating degree days = $\sum_i^I (17C - T_i)$, with T_i equaling the daily mean temperature at day i.
[6]See BDH (2010) for a distribution of heating systems in the German building stock.
[7]Micro-data for subsidies for energetic building modernizations received by households are not covered by the SOEP.
[8]KfW stands for Kreditanstalt für Wiederaufbau (Reconstruction Credit Institute)) and is a German government-owned development bank.
[9]For further details on the subsidy programs see Section Appendix D in the Appendix.
[10]An average of the program periods is used to account for the different time lags between approval of the subsidy and the completion of the renovation.

Table 1: Overview of variables

Name	Description
dependent	
dwelling modernizations	1 if household installed new window or made other major modernizations in previous year, 0 else
log. heat. exp. per m^2	logarithm of average annual heating and warm water expenditure per m^2
independent	
household characteristics:	
owner-occupied	1 if household is owner of the dwelling, 0 else
log. of adj. income	logarithm of disposable monthly household income
household type	categorial variable with
1	one person household
2	childless couple
3	single parent
4	couple with children $\leq$ 16 years
5	couple with children $>$ 16 years
6	couple with children $\leq$ and $>$ 16 years
7	multiple generation household
8	other combination
dwelling characteristics:	
construction period	categorial variable with
1	built before 1918
2	built in 1918–1948
3	built in 1949–1971
4	built in 1972–1980
5	built in 1981–1990
6	built in 1991–2000
7	built in 2001–2010
number of relocations	number of relocations between 1992–2010
room	number of rooms $> 6m^2$
need of renovation	condition of dwelling (1–4; 1 good, 4 renovation necessary)
modernized	1 if dwelling has been modernized, 0 else
treated household group 1	1 for households that modernized between 1996 and 2002, 0 else
treated household group 2	1 for households that modernized between 2003 and 2010, 0 else
macro-indicators:	
subsidy ratio	average subsidy as a proportion of average modernization spendings by program (interest rate reductions, or lump-sum subsidies)
log. of gas price	logarithm of gas price index for residential heating (2005 = log(100))
HDD	heating degree days published by ECA&D
year dummies	year dummies for each other year between 1992 and 2010
state dummies	state dummies for ten different states

Statistical Office (DESTATIS).
Two main program periods are differentiated. The first program period of the CO_2-reduction programs is 1996–2002 and the second program period is 2003–2010 when the dwelling modernization program provided additional subsidies. The CO_2-reduction program has been modified in 2001 and the dwelling modernization program has been adapted in 2005. Therefore, the subsidy ratio varies over the years 1996–2000, 2001–2002, 2003–2004, 2005–2010 and over the ten different Western German states[11]. Figure 1 shows the development of the subsidy ratio for the states and years covered in the analysis. Moreover, dummies for the ten different states as well as year dummies for the years 1992–2010 are included.

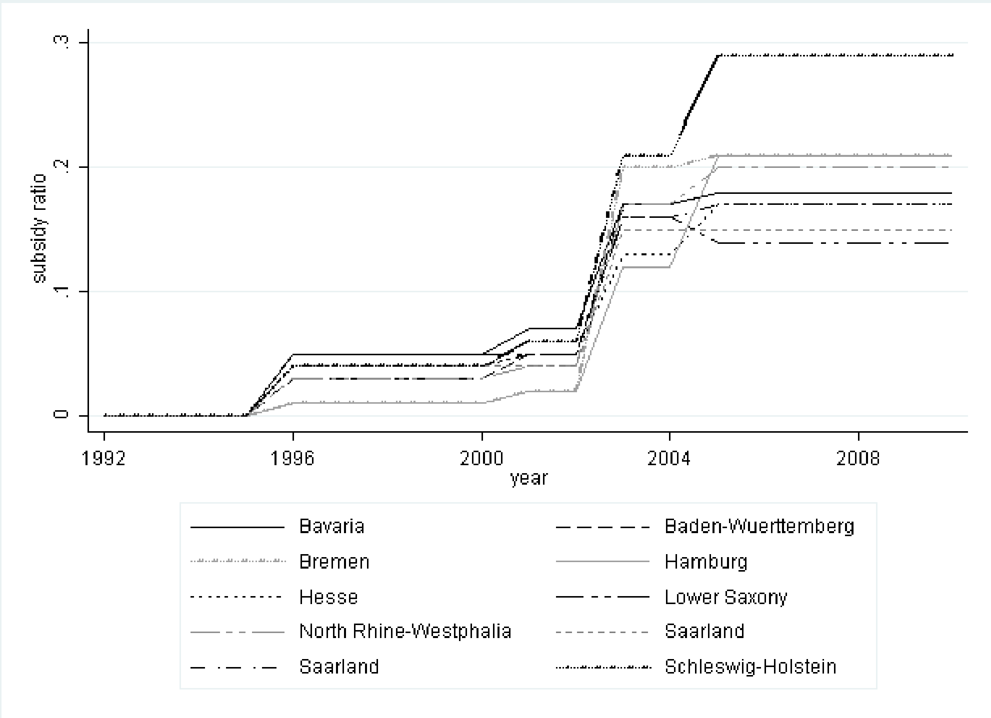

Figure 1: Average subsidies per state

4.2. Heating expenditure and dwelling modernization

Germany is a special case concerning the tenancy structure of dwellings. Only about 50% of the dwellings are actually owned by the residents (see Figure 2). Renovations in rented dwellings are made by landlords. Several studies have shown the importance of accounting for the ownership status to explain investments and renovations (Gebhardt, 2012), as well as heating expenditures (Rehdanz, 2007), in German dwellings. Figure 3 shows the development of the average heating expenditure per square meter between 1992 and 2010 for all households together and for owners and tenants separately. The level of the average heating expenditure of an owner is far below the average tenant's expenditure. However, the development of the heating expenditure follows a similar pattern for owners and tenants. Heating expenditure decreased after 1996 and increased again consistently from 2000 onwards. The development of the gas price index (2005 = 100) indicates that increases in heating expenditures mainly result from increases in gas price increases.

[11]The states included are Baden-Wuerttemberg, Bavaria, Bremen, Hamburg, Hesse, Lower Saxony, North Rhine-Westphalia, Rhineland-Palatinate, Saarland and Schleswig-Holstein. Berlin is excluded because of the aforementioned potential impacts of the reunification.

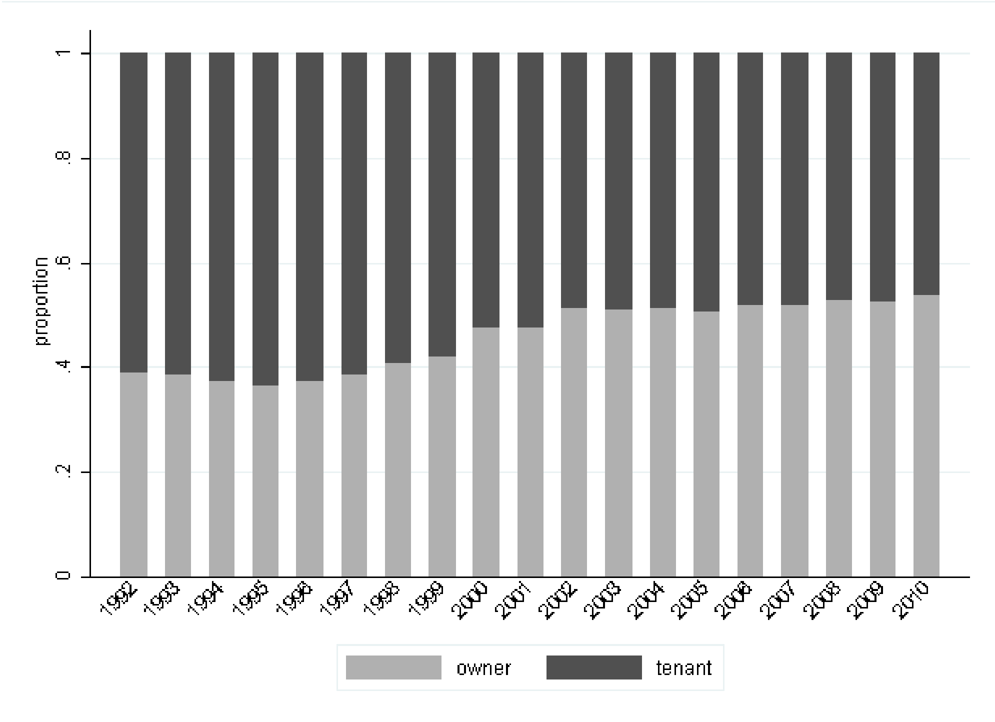

Figure 2: Percentage of households with owners or tenants in Western Germany

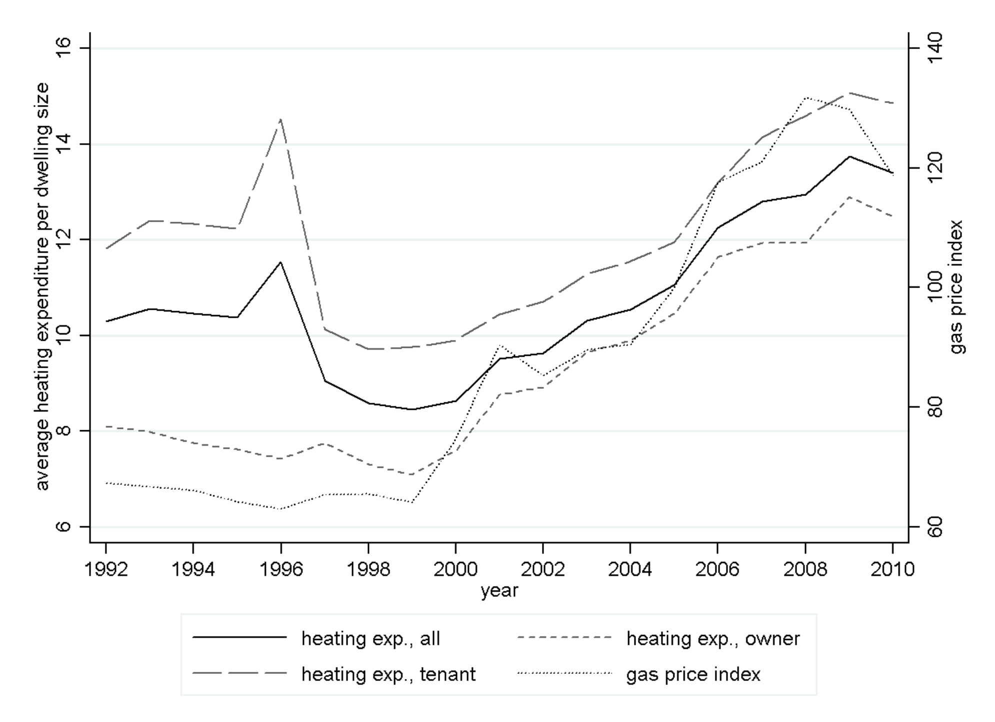

Figure 3: Heating expenditure and gas price development

Figure 4 shows the subsidy ratio of 1-7% percent for renovation spendings in the first program phase until 2002. The subsidy ratio increases significantly to 12-29% during the second period reaching the peak after 2003. Figure 4 also depicts the share of dwellings that are modernized in a respective year as well as real heating expenditures for owners and tenants separately. The share of modernized dwellings is relatively stable between 1996 and 1999, decreases in 2000 and increases constantly after 2003, indicating a quantity effect of the subsidy, i.e. that the subsidy may have a positive impact on the number of renovations. Moreover, the real heating expenditures, i.e. accounting for changes in gas price levels, follow almost the opposite pattern over time. Figure 4 shows a strong decrease in real heating expenditures between 1996 and 2000, and a continuing decrease after 2003. Thus, it is worth analyzing if the subsidies effectively promote dwelling modernization and cause lower heating energy consumption (Hypothesis 1 and Hypothesis 2).

Furthermore, the proportion of modernizations made in owner-occupied dwellings is considerably higher than in tenant-occupied dwellings. Gebhardt (2012) shows that renovations are more frequent if the occupant owns the dwelling (as observed in the data) and in turn cause lower heating expenditures for owners. The difference in modernizations made in owner- and tenant-occupied dwellings and the lower energy expenditures for owners indicating lower insulation give reason to Hypothesis 3. The landlord-tenant problem may broaden the energy efficiency gap and impact the effectiveness of the subsidies.

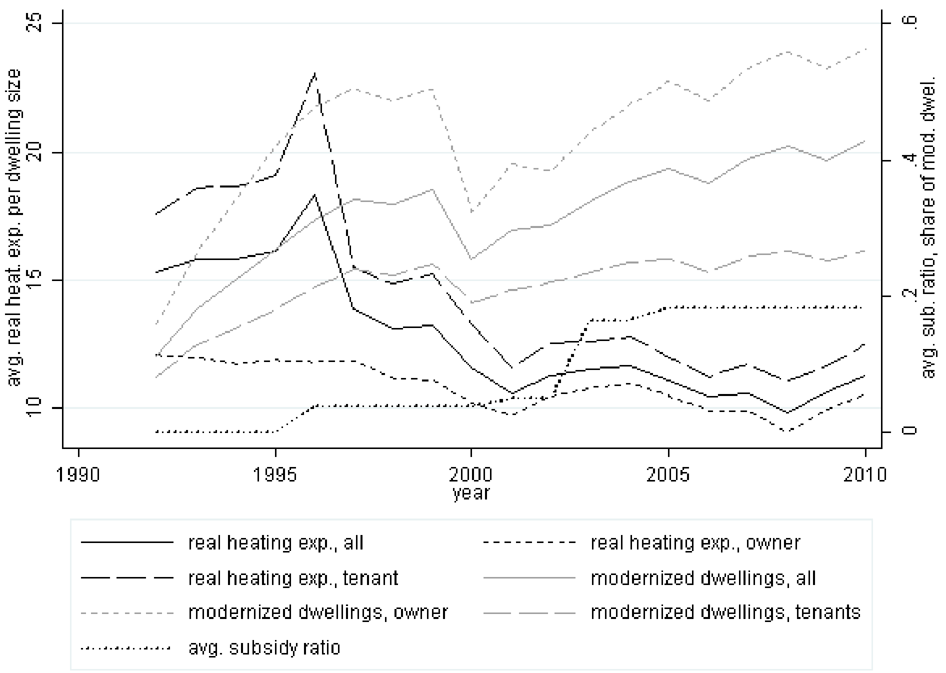

Figure 4: Average subsidy payments for different treatment periods and real heating expenditure

A comparison of the disposable income of owners and tenants, as presented in the boxplots in Figure 5, reveals that the disposable income of owners tends to be significantly greater than that of tenants. Over all years, 75% of the tenants have less disposable income than the average owner. Baker et al. (1989) also find a significant correlation between homeownership and income.

In a functioning renting market, a landlord would modernize a dwelling as long as the rent could adapt according to the tenant's payment abilities. The income of a tenant thus may indicate a potential credit barrier to investments in energy efficiency. On the contrary, the high income of owners and the high proportion of subsidies received by owners – more than 50% of all subsidies in 2009[12] – may give reason to

[12]See Clausnitzer et al. (2010).

analyze whether subsidies may be a windfall in case of a high a priori willingness to pay.

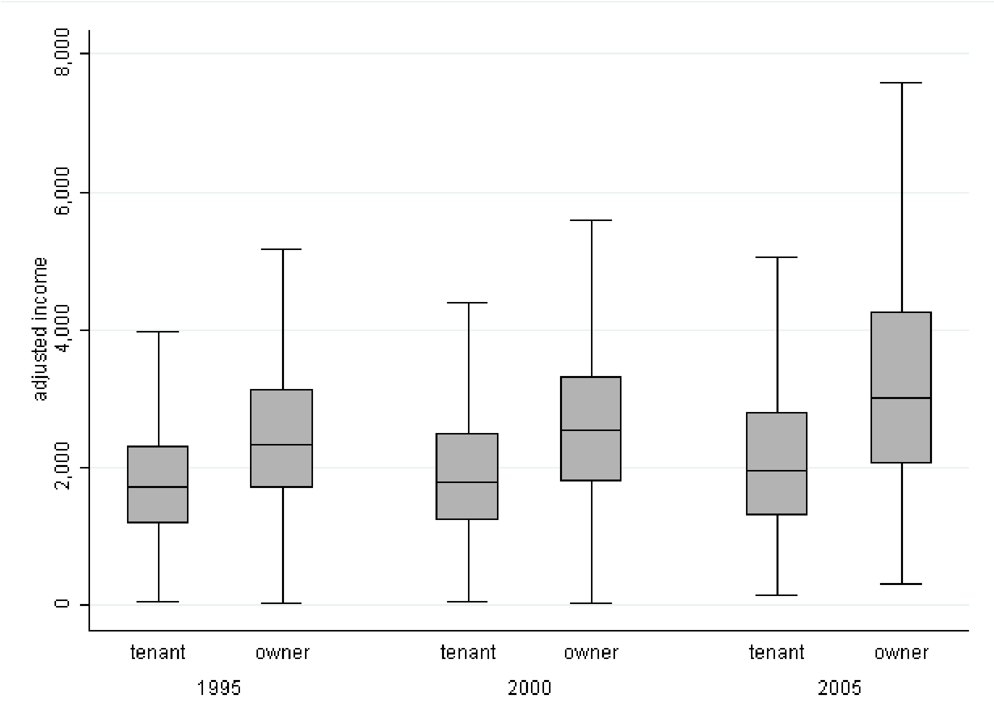

Figure 5: Boxplots of disposable monthly income in Euros for households with owners or tenants

5. Estimation Approach

The estimation objective is to analyze the effects of the German subsidy program on energy efficiency and to test the hypotheses presented in Section 3. The subsidy program is meant to give incentives to invest in energy efficiency thus reducing energy consumption. The subsidy program can be effective by increasing the number of investments in energy efficiency (quantity effect) and/or by improving the quality of the investments in terms of energy efficiency (quality effect). In the first model approach, the impact of the subsidy on the probability of dwelling modernizations is analyzed to capture the quantity effect (see Figure 6 arrow A). In the second approach, the impact of these dwelling modernizations investments on energy expenditures[13] is investigated (see Figure 6 arrow B). A differences-in-differences-in-differences (DDD) approach is applied which allows for an identification of the impact of dwelling modernizations made during the subsidy periods and estimates the effect B. Thus, the second approach measures the quality effect, i.e. whether dwelling modernizations reduce energy expenditures dependent on the prevailing subsidy program. Moreover, both approaches, A and B control for the ownership status in order to identify potential differences in the dwelling modernization and energy consumption behavior in owner- and tenant-occupied dwellings.

[13]Energy expenditures and energy consumption are used as synonyms because prices are controlled for while estimating the impacts on energy expenditures.

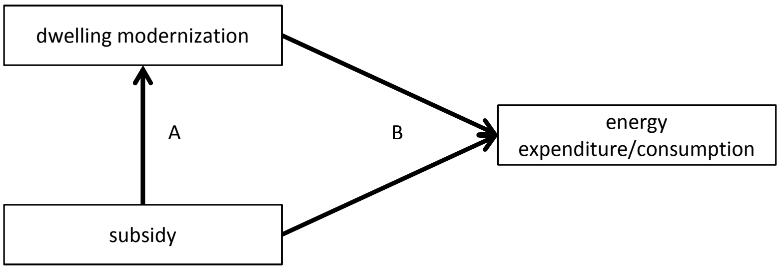

Figure 6: Estimation strategy

5.1. Number of investments in energy efficiency

First, an examination is performed to determine to what extent the number of dwelling modernizations can be explained by household characteristics and subsidies. The model estimates:

$$z_{i,t} = \alpha + \beta h_{i,t} + \gamma s_{r_i,p_t} + \delta_0 d_{0,i,t} + \delta d_{0,i,t} \cdot \gamma s_{r_i,p_t} + \delta_r d_{r_i} + \delta_t d_t + \epsilon_{i,t}, \tag{1}$$

where $z_{i,t} \in \{0,1\}$ describes whether a dwelling is modernized, $h_{i,t}$ is a vector of time-variant household and dwelling characteristics, s_{r_i,p_t} is the subsidy ratio in state r_i (with each household i being a part of state $r_i \in R$) in the subsidy program period p_t (for the years $t \geq 1996$, as a part of the program period $p_t \in P$), $d_{0,i,t}$ is a dummy variable indicating the ownership of the dwelling and $\epsilon_{i,t}$ is an error term that is assumed to be independent and identically distributed (i.i.d.). To control for time and regional effects, dummies are included for the different states (d_{r_i}) and for the different years (d_t). Two ordinary least squares models (OLS) with and without state dummies and a probit model are implemented. To avoid an underestimation of standard errors (due to serial correlation), all standard errors are robust and clustered at the household level.[14]

5.2. Heating energy expenditures

The second analysis investigates the impacts of the investments in energy efficiency on heating energy expenditures. The following panel data model is introduced:

$$\begin{aligned} log(y_{i,t}) &= \alpha + \beta h_{i,t} + \gamma_1 log(p_t) + \gamma_2 w_{s_i,t} + \delta d_{i,t}^{DDD} + \delta_r d_{r_i} + \delta_t d_t + \epsilon_{i,t} \qquad (2)\\ \text{with } \delta d_{i,t}^{DDD} &= \delta_0 d_{0,i,t} + \delta_1 d_{1,i,t} + \delta_2 d_{2,i,t} + \delta_3 d_{3,i,t} + \delta_4 d_{1,i,t} \cdot d_{2,i,t} + \delta_5 d_{1,i,t} \cdot d_{3,i,t}\\ &+ \delta_6 d_{0,i,t} \cdot d_{1,i,t} + \delta_7 d_{0,i,t} \cdot d_{2,i,t} + \delta_8 d_{0,i,t} \cdot d_{3,i,t}\\ &+ \delta_9 d_{0,i,t} \cdot d_{1,i,t} \cdot d_{2,i,t} + \delta_{10} d_{0,i,t} \cdot d_{1,i,t} \cdot d_{3,i,t}, \end{aligned}$$

where $log(y_{i,t})$ is the logarithm of monthly heating expenditures, $h_{i,t}$ is the matrix of time-variant household characteristics, $log(p_t)$ is the vector of the logarithm of gas prices that vary over time (but not over households), $w_{s_i,t}$ are the heating degree days that vary over states and time, d_{r_i} are state dummies and d_t year dummies. The variable $\epsilon_{i,t}$ is the error term, assumed i.i.d.

The estimation strategy is a differences-in-differences-in-differences (DDD) approach. The presented DDD approach controls for treated groups of households, modernizations and ownership status in order to ensure unconfoundedness so that conditional on these controls treatment assignment is essentially randomized. The matrix $\delta d_{i,t}^{DDD}$ presents the dummy variables and dummy interaction variables of the (DDD) approach. These dummy variables include dummies for dwelling modernizations, the treated household types and the ownership status. Specifically, the dummy variable $d_{0,i,t}$ indicates whether a dwelling is

[14]Standard errors based on other clusters such as on a state, year or state and year level have been estimated and the clusters at the household level turned out to be the highest and thus the most conservative.

owner-occupied and $d_{1,i,t}$ indicates whether the dwelling has been modernized in previous years. $d_{2,i,t}$ identifies the treated households of the first subsidy period and $d_{3,i,t}$ the treated households of the second subsidy period. The *treated household group 1* indicates those households that modernize during the first subsidy period 1996–2002. The *treated household group 2* are those households that modernize during the second subsidy period 2003–2010. Households that apply for a subsidy may be households that invest more frequently in general or care more than average about their energy consumption and thus may already have lower heating expenditures before the renovation during the subsidy programs (or the contrary). Hence, the dummies $d_{2,i,t}$ and $d_{3,i,t}$ control for general differences in energy expenditures between the treated and non-treated household types.

The interaction terms $d_{1,i,t} \cdot d_{2,i,t}$ and $d_{1,i,t} \cdot d_{3,i,t}$ indicate whether a treated household type has modernized. As the ownership status is additionally included in the last three interaction terms, the first three interaction terms without $d_{0,i,t}$ are included to measure the effects in tenant-occupied dwellings. The landlord-tenant problem may result in a significant difference between heating expenditures of owners and tenants and Figure 3 and Figure 4 in Section 4.2 already gave an indication for this assumption. Therefore, the interaction term $d_{0,i,t} \cdot d_{1,i,t}$ identify modernizations made by owners. The interaction terms $d_{0,i,t} \cdot d_{1,i,t} \cdot d_{2,i,t}$ and $d_{0,i,t} \cdot d_{1,i,t} \cdot d_{3,i,t}$ indicates treated households that have modernized and are owners.

The DDD approach and the inclusion of two treatment periods identify further pre-existing differences in trends and serve to cope with the parallel trend assumption that is assumed to hold for the development of energy expenditures and modernizations between the considered households.

A simplified interpretation of the effects of the DDD approach is presented in Table 2:

Table 2: Interpretation of dummy variables in the differences-in-differences-in-differences approach

δ_0	$= \overline{y}_{own.} - \overline{y}_{!own.}$
δ_1	$= \overline{y}_{mod.} - \overline{y}_{!mod.}$
$\delta_{2,3}$	$= (\overline{y}_{treat_j} - \overline{y}_{!treat_j})$
$\delta_{4,5}$	$= (\overline{y}_{treat_j,mod.} - \overline{y}_{treat_j,!mod.}) - (\overline{y}_{!treat_j,mod.} - \overline{y}_{!treat_j,!mod.})$
δ_6	$= (\overline{y}_{mod.,own.} - \overline{y}_{mod.,!own.}) - (\overline{y}_{!mod.,own.} - \overline{y}_{!mod.,!own.})$
$\delta_{7,8}$	$= (\overline{y}_{treat_j,own.} - \overline{y}_{treat_j,!own.}) - (\overline{y}_{!treat_j,own.} - \overline{y}_{!treat_j,!own.})$
$\delta_{9,10}$	$= \Big[(\overline{y}_{treat_j,mod.,own.} - \overline{y}_{treat_j,mod.,!own.}) - (\overline{y}_{treat_j,!mod.,own.} - \overline{y}_{treat_j,!mod.,!own.})\Big]$
	$- \Big[(\overline{y}_{!treat_j,mod.,own.} - \overline{y}_{!treat_j,mod.,!own.}) - (\overline{y}_{!treat_j,!mod.,own.} - \overline{y}_{!treat_j,!mod.,!own.})\Big]$

For $\delta_2, \delta_4, \delta_7, \delta_9$, the subscript j refers to the first subsidy period 1996–2002. For $\delta_3, \delta_5, \delta_8, \delta_{10}$, the subscript j refers to the second subsidy period 2003–2010. The variable $\overline{y}$ reflects the average heating energy expenditure of the respective group. The term *own.* indicates ownership of the dwelling and !*own.* refers to tenants. The term *mod.* identifies households that modernized their dwellings and !*mod.* describes households that did not. The term $treat_j$ indicates the households that modernized in the subsidy program period in general (not only during the subsidy period) and $!treat_j$ are all other households.

Thus, $\delta_{9,10}$ can be interpreted as the triple deviation in the heating expenditures of a) owner and tenants, b) households that modernized c) treated households. The time and regional effects on energy expenditure are additionally controlled for through d_{r_i} and d_t.

In the first step, the model presented in Equation 3 is estimated without the DDD approach, i.e. excluding the matrix $\delta d_{i,t}^{DDD}$, and is additionally separately estimated for only owners and only tenants. These reduced models are estimated to analyze the impact of the household and dwelling characteristics on energy consumption and to get an idea of the different energy consumption behavior and price elasticities of owners and tenants.

In the second step, the model in Equation 3 is estimated in an ordinary least squares approach (OLS) with and without state dummies, and then in a feasible least squares approach (FGLS) again with and without state dummies. All standard errors are robust and clustered at the household level to avoid an inconsistent estimation of standard errors due to a serial intra-household correlation (see Bertrand et al. (2004)). The FGLS estimation capturing the assumption of serial correlation in the variance covariance matrix, additionally serves to check the robustness of the results.

6. Results

6.1. Impacts on dwelling modernizations

Previous studies presented in Section 2 have shown the importance of accounting for socio-economic and dwelling characteristics in analyzing household investments in energy efficiency. Therefore, the impacts of these characteristics are first described and the effects of the subsidies and the ownership status on renovations are then investigated.

6.1.1. Impacts of socio-economic and dwelling characteristics

Table 3 presents the determinants of dwelling modernizations based on Equation 1. The mean dwelling modernization rate in the dataset for all households between 1992 and 2010 is 5.9% (see Table C.5), which is only slightly impacted by socio-economic and dwelling characteristics. A 1% increase in income increases the probability of dwelling modernization by only 0.01 percent on average over all households. These results indicate that credit barriers may not play a major role.

The categorical variable *household type* is an indicator for the household size and has larger values for more family members. The results mirror that the larger the household, the lower the probability of dwelling modernizations.

The modernization state of buildings from older vintage classes may probably be lower. The effect of the *construction period* variable shows that this holds true. The effect is significant and reflects a significantly lower probability of younger dwellings being modernized than those from earlier construction periods.

The number of relocations increases the probability of modernizations by 0.79 (model (3)) to 0.85 (model (1)) percentage points, i.e. the more often households relocate, the more probable it is that they will invest in their dwelling. The result seems surprising as one may assume that a household that frequently moves is less likely to invest in their dwelling. However, households in Germany seldomly relocate. 69% of all households in the sample never move and 93% move not more than twice. Thus, the probability of renovations is higher when households move into a new location rather than stay in their current building. There may be various reasons for relocaters to invest, such as further socio-economic characteristics that are not covered in the model (e.g. the type of job).

Dwellings with more rooms and more windows exhibit a higher probability of dwelling modernizations. The probability increases by 0.33 (model (3)) to 0.37 (model (2)) percentage points for each additional room. As window modernizations are a major part of dwelling modernizations, the more rooms that are in a dwelling, the more windows it has, thus increasing the need and probability of modernization. In addition, the worse the condition of the dwelling evaluated by the household (*need of renovation*) the higher the probability of dwelling modernizations.

6.1.2. Impacts of subsidies and ownership status

To evaluate Hypothesis 1 and 3 presented in Section 3, the impacts of ownership status and subsidies spent are analyzed.

The impacts of the *subsidy ratio* (proportion of subsidies to modernization spendings) on the number of modernizations in tenant-occupied dwellings is not significant in all models. Only a small proportion of dwellings is modernized each year and the modernization rates only change slightly. The probability of renovation of tenant-occupied dwellings (made by landlords) thus seems to be mainly impacted by socio-economic and

Table 3: Results Estimation A: Probability of dwelling modernizations

dwelling modernizations	OLS (1)	OLS (2)	Probit (3)	AME[1], Probit (3)
owner-occupied	0.0115***	0.0115***	0.0917***	0.0115***
	(0.0023)	(0.0023)	(0.0185)	(0.0025)
log. of adj. income	0.0108***	0.0106***	0.0957***	0.0111***
	(0.0012)	(0.0012)	(0.0109)	(0.0013)
household type	-0.0011***	-0.0012**	-0.0083**	-0.0010**
	(0.0004)	(0.0004)	(0.0035)	(0.0004)
construction period	-0.0075***	-0.0075***	-0.0652***	-0.0075***
	(0.0004)	(0.0004)	(0.0036)	(0.0004)
number of relocations	0.0085***	0.0084***	0.0684***	0.0079***
	(0.0007)	(0.0007)	(0.0048)	(0.0006)
number of rooms (> 6 m^2)	0.0036***	0.0037***	0.0282***	0.0033***
	(0.0005)	(0.0005)	(0.0036)	(0.0004)
need of renovation	0.0034**	-0.0034	0.0291***	0.0034***
	(0.0013)	(0.0013)	(0.0111)	(0.0013)
subsidy ratio	0.0089	-0.0202	-0.0235	-0.0027
	(0.0411)	(0.0314)	(0.3480)	(0.0402)
subsidy ratio, owner	0.0304*	0.0308*	0.3876***	0.0448***
	(0.0166)	(0.0166)	(0.1425)	(0.0165)
Observations	125686	125686	125686	
Clusters	16870	16870	16870	
Overall (Pseudo-) R^2	0.0071	0.0068	0.0159	
Wald-Test (Probit/) F-Test (OLS)	31.03	38.93	1095.16	
Prob. > χ^2 (Probit) / Prob. > F (OLS)	0.000	0.000	0.000	

[1] AME: Average Marginal Effects
Robust standard errors are clustered by households and are reported in parentheses.
All models include a constant and year dummies.
Models (1) and (3) additionally include state dummies.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

dwelling characteristics. The number of dwelling modernizations by landlords is not impacted by increasing subsidy levels, which may contradict Hypothesis 1. However, although the number of renovations does not increase through the subsidy, the quality might (Hypothesis 2). The quality impact is investigated in the results of the next section.

The models show the significant impact of ownership status on the probability of dwelling modernizations. The probability of dwelling modernizations increases by about 1.2 percentage points, i.e. almost 20% of the average dwelling modernization rate of 5.9%, when the dwelling is owner-occupied. The resulting effect confirms the results of other studies (Gebhardt, 2012) that there exists an underinvestment in buildings that are not occupied by the owners. Thus, this landlord-tenant problem is prominent in the German building stock and has essential impacts on investments in energy efficiency, supporting Hypothesis 3.

In accounting for the higher renovation probability owners generally, have a 1 percentage point increase in the subsidy ratio increases the probability of dwelling modernizations by 0.030 (model (1)) to 0.045 (model (3)) percentage points. Thus, the effect of the subsidy on renovations in owner-occupied dwellings is small. In addition, the effect is only slightly significant in the OLS models. Hence, the results show that the subsidy increased the incentives to renovate only for households of homeowners, which further supports Hypothesis 3.

In summary, it can be concluded that the quantity effect of the subsidy, i.e. the subsidy increases the number of dwelling modernizations, only occurs for homeowners. During times of high subsidies, especially during the second program period, the probability of renovations only increases in owner-occupied dwellings. Landlords did not renovate more buildings with an increasing subsidy. However, if the landlord had decided to invest, the insulation level may have increased. In the next subsection, it is investigated whether this is truly the case.

6.2. Impacts on heating energy consumption

After the analysis of the quantity effect of the subsidy on dwelling modernization, this section analyzes the quality effect and attempts to answer the question whether renovations made during subsidy program periods decreased energy consumption. Socio-economic and dwelling characteristics again play a major role and are controlled for. The first subsection describes their effects. The impacts of the renovations during subsidy periods based on the DDD approach are presented in the second subsection.

6.2.1. Impacts of socio-economic and dwelling characteristics

Heating expenditures[15] of households depend on a variety of household and dwelling conditions, as well as energy prices and heating degree days. These variables need to be controlled for in order to identify the impacts of modernizations with respect to the subsidy programs. Therefore, the first three OLS models in Table 4 neglect the DDD approach and estimate only the impact of the control variables on heating expenditures. Figure 2 shows the large difference in the heating expenditures in owner- and tenant-occupied dwellings. To demonstrate the different heating behaviors, separate models are estimated for a sample of only owners (in model (2)) and only tenants (in model (3)). Model (1) estimates the effects of the control variables for the whole sample. The effects are found to be quite robust in the whole sample over all models ((1), (4) - (7)) and explain between 17.5% (model (1)) and 18.5.% (model (2)) of the variation of total household warm water and heating expenditures. This is in the range of other studies. Rehdanz (2007) explains between 17% and 27% of the variation in heating expenditures and Brounen et al. (2012) explain about 16% of the variance in gas consumption in their basic model.

Heating expenditures increase as the number of heating degree days (*HDD*) increases, i.e. in colder years, for the whole sample. The impact of the heating degree days is however not significant for the sample of only owners ((model (2)), which may indicate a better insulation of owner-occupied dwellings. Cold days affect the heating expenditures in tenant-occupied dwellings to a larger extent.

The results in Table 4 present the price elasticity of expenditure on average over all households (models (1), (4) - (7)) as well as for owners (model (2)) and tenants (model (3)) separately. The price elasticity of

[15] Controlling for the price effect, the terms ‘expenditures’ and ‘consumption’ are used synonymously.

Table 4: Results Estimation B: Logarithm of heating expenditure per dwelling size

	OLS, All	OLS, Owner	OLS, Tenant	OLS, All		FGLS, All	
log. heat. exp. per m^2	(1)	(2)	(3)	(4)	(5)	(6)	(7)
owner-occupied (d_0)	-0.1801***			-0.1995***	-0.1992***	-0.2229***	-0.2234***
	(0.0083)			(0.0100)	(0.0100)	(0.0104)	(0.0104)
HDD	1.58e-07***	-1.60e-08	2.98e-07***	1.52e-07***	1.43e-07**	1.32e-07***	1.34e-07***
	(5.13e-08)	(6.48e-08)	(7.99e-08)	(5.10e-08)	(6.18e-08)	(4.43e-08)	(4.33e-08)
log. of gas price	0.5706***	0.8255***	0.2537***	0.5661***	0.5673***	0.5804***	0.5803***
	(0.0286)	(0.0396)	(0.0408)	(0.0287)	(0.0287)	(0.0274)	(0.0274)
log. of adj. income	0.0361***	0.0534***	0.0163**	0.0360***	0.0367***	0.0244***	0.0250***
	(0.0065)	(0.0094)	(0.0080)	(0.0065)	(0.0065)	(0.0055)	(0.0055)
household type	0.0069***	0.0002	0.0212***	0.0071***	0.0069***	0.0091***	0.0089***
	(0.0021)	(0.0030)	(0.0027)	(0.0021)	(0.0021)	(0.0017)	(0.0017)
construction period	-0.0409***	-0.0567***	-0.0156***	-0.0416***	-0.0421***	-0.0344***	-0.0348***
	(0.0023)	(0.0032)	(0.0029)	(0.0023)	(0.0023)	(0.0024)	(0.0024)
number of relocations	-0.0353***	-0.0691***	-0.0065**	-0.0352***	-0.0352***	-0.0485***	-0.0485***
	(0.0030)	(0.0056)	(0.0030)	(0.0030)	(0.0030)	(0.0032)	(0.0032)
number of rooms (> 6 m^2)	-0.0666***	-0.0613***	-0.0880***	-0.0666***	-0.0667***	-0.0678***	-0.0679***
	(0.0025)	(0.0030)	(0.0043)	(0.0025)	(0.0025)	(0.0024)	(0.0024)
need of renovation	0.0211***	0.0285***	0.0232***	0.0215***	0.0220***	0.0140***	0.0143***
	(0.0057)	(0.0106)	(0.0063)	(0.0057)	(0.0057)	(0.0043)	(0.0043)
modernized (d_1)				0.0357**	0.0364**	0.0445***	0.0450***
				(0.0156)	(0.0155)	(0.0114)	(0.0114)
treated household group 1 (d_2)				-0.0401**	-0.0401**	-0.0347**	-0.0352**
				(0.0166)	(0.0166)	(0.0162)	(0.0162)
treated household group 2 (d_3)				-0.0675***	-0.0697***	-0.0900***	-0.0906***
				(0.0177)	(0.0177)	(0.0150)	(0.0150)
modernized x treated household group 1 ($d_1 \cdot d_2$)				-0.0471**	-0.0482**	-0.0557***	-0.0565***
				(0.0200)	(0.0200)	(0.0151)	(0.0151)
modernized x treated household group 2 ($d_1 \cdot d_3$)				-0.0492***	-0.0493***	-0.0481***	-0.0485***
				(0.0188)	(0.0187)	(0.0146)	(0.0146)
modernized x owner				-0.0881***	-0.0883***	-0.0975***	-0.0981***
				(0.0199)	(0.0198)	(0.0144)	(0.0144)
treated household group 1 x owner ($d_0 \cdot d_2$)				0.0430*	0.0426*	0.0481**	0.0486**
				(0.0232)	(0.0232)	(0.0221)	(0.0221)
treated household group 2 x owner ($d_0 \cdot d_3$)				0.0907***	0.0936***	0.1258***	0.1271***
				(0.0221)	(0.0220)	(0.0197)	(0.0197)
modernized x treated household group 1 x owner ($d_0 \cdot d_1 \cdot d_2$)				0.1271***	0.1283***	0.1362***	0.1373***
				(0.0258)	(0.0258)	(0.0200)	(0.0200)
modernized x treated household group 2 x owner ($d_0 \cdot d_1 \cdot d_3$)				0.1292***	0.1291***	0.1299***	0.1306***
				(0.0221)	(0.0221)	(0.0176)	(0.0176)
Observations	102535	56022	46513	102535	102535	102535	102535
Clusters	15421	8271	8885	15421	15421	15421	15421
Overall (Pseudo-) R^2	0.1749	0.1849	0.1133	0.1773	0.1760	0.1759	0.1748
F-test (OLS)/Wald-test (FGLS)	333.56	208.74	118.81	248.64	324.83	10886.44	10747.69
P>F(OLS)/P>χ^2(FGLS)	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Robust standard errors are clustered by households and are reported in parentheses.
All models include a constant and year dummies for two consecutive years.
Model (1),(3),(5) and (6) additionally include a state dummies.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

energy-demand $\epsilon_{q,p}$ can be derived from the price elasticity of expenditure $\frac{\partial e(p)}{p}\frac{p}{e}$: For a single household, the gas price is exogenous such that the heating expenditures $e(p)$ can be described as $e(p) = pq(p)$, where p is the price and $q(p)$ is the heating energy consumed. Therefore:

$$\frac{\partial e(p)}{\partial p}\frac{p}{e} = \left(q(p) + p\frac{\partial q(p)}{\partial p}\right)\frac{p}{pq(p)} = 1 + \epsilon_{q,p} \tag{3}$$

$$\epsilon_{q,p} = \frac{\partial e(p)}{\partial p}\frac{p}{e} - 1 \tag{4}$$

$$\text{with} \quad \epsilon_{q,p} = \frac{\partial q(p)}{\partial p}\frac{p}{q(p)} \tag{5}$$

The effect of gas prices is significant with an price elasticity of expenditure of 82.55% (model (2)) to 25.37% (model (3)) on average over all households. Thus, for owners, the price elasticity of energy-demand is approximately $\epsilon_{q,p} = \frac{\partial e(p)}{p}\frac{p}{e} - 1 = 0.83 - 1 = -0.17$ and for tenants $\epsilon_{q,p} = 0.25 - 1 = -0.75$. Tenants with higher mean heating expenditures per square meter (see Figure 3) react more elastic to increases in energy price compared to owners, who exhibit a very low price elasticity of demand. For tenants, a 10% increase in energy prices results in a 7.5% reduction of energy consumed. According to Khazzoom (1980), a high demand elasticity indicates a larger rebound-effect. Hence, investments in energy efficiency for tenant-occupied dwellings may be less effective in increasing energy-savings. The price elasticity of tenants can be ascribed to the landlord-tenant problem: Since the landlord cannot internalize his investment costs in the rents paid by tenants, the tenant benefits from the energy savings but does not bear the investment costs. The adjusted income has a significant impact on heating expenditures. A 1% increase in income increases the heating expenditures per m^2 by 0.024% (model (6)) to 0.037% (model (5)) on average for all households. A 1% higher income of owners increases energy expenditures, by 0.053%, compared to tenants who only exhibit an expenditure income elasticity of 0.016. These differences in income elasticities indicate to the landlord-tenant problem. Higher income of tenants does not increase the insulation level and decrease energy consumption to the same extent as the higher income of homeowners does.

Impacts of the household composition (*household type*) are more relevant in explaining heating expenditures than dwelling modernizations. Brounen et al. (2012) have already shown the importance of including the household composition and other socio-economic factors in the explanation of residential gas consumption. The heating expenditures increase as the number of household members increases. However, the impact of the number of household members is not significant for owner-occupied dwellings, which may be traced back to higher insulation standards.

Heating expenditures are significantly lower for dwellings from later rather than from earlier construction periods, especially the effect is stronger when considering owner-occupied dwellings. The *number of relocations* has a negative and significant impact on heating expenditures, as opposed to a positive impact on the probability of dwelling modernizations, as previously discussed. The previous section shows that households which relocate tend to invest more in energy efficiency, thus significantly decreasing heating expenditures. The negative impact is considerably higher for owners than for tenants. Investments made by owners thus appear to be more energy-efficient. Moreover, it may be that households, and especially owners, relocate to more energy-efficient dwellings. The *number of rooms* decreases the heating expenditures per square meter by 6.1% (model (2)) to 8.8% (model (3)). Furthermore, the *need for renovation*, as assigned by the interviewed household members, increases heating expenditures significantly.

In summary, the estimation results have shown that the heating expenditures of owners and tenants differ significantly and that tenants tend to be significantly more price sensitive. The next section analyzes the impacts of ownership status and the impacts of modernizations made during subsidy periods.

6.2.2. Impacts of ownership status and modernizations during subsidy periods

In addition to the quantity effect investigated in Section 6.1.2, this section examines the quality effect (Hypothesis 2), i.e. the impact on energy consumption of modernizations made by owners and landlords during subsidy periods. The analysis of the impact of the subsidies on the number of dwelling modernizations

presented in Section 6.1.2 shows that the subsidies only have a significant impact on renovations when made by homeowners. This section attempts to further analyze Hypothesis 3, i.e. whether the landlord-tenant problem causes underinvestment in energy efficiency and reduces the effectiveness of subsidies.
In general, heating expenditures are by 18% (model (1)) to 22.3% (model (7)) significantly lower in owner-occupied dwellings. Homeowners tend to renovate buildings more energy efficiently than landlords do.

In comparison to models (1) to (3), models (4) to (7) additionally include the dummy variables and the interaction of dummy variables in the DDD approach. In general, modernized tenant-occupied (*modernized*) dwellings exhibit significantly higher heating expenditures than other dwellings. Tenant-occupied dwellings seem to be poorly insulated, which, despite being renovated, still cause high energy consumption levels. Putting it differently, it appears that especially poorly insulated tenant-occupied dwellings are modernized and still exhibit high energy consumption levels after the modernization.

The tenants who belong to the *treated household group 1* (whose dwellings are modernized during the first program period) have significantly lower heating expenditures on average compared to other households. Given these conditions, modernizations made within the period 1996–2002 additionally decrease their heating expenditures by 4.7% (model (4)) to 5.7% (model (7)). Tenants who are part of the *treated household group 2* already exhibit lower heating expenditures than other households in general. Their heating expenditures are further reduced by 4.9% by renovation.

Thus, a landlord-tenant problem is present. However, the subsidy programs appear to have a positive impact on investments in energy efficiency made by landlords, despite the landlord-tenant problem. These findings provide a proof for Hypothesis 2 and 3. Moreover, the significant effects of the dummies that control for the household types living in dwellings that were modernized during the sample years, presents the importance of the DDD approach. The DDD approach controls for energy consumption behavior which would have otherwise affected the estimators of the modernizations made during the subsidy periods.

Heating expenditures in modernized owner-occupied dwellings are by 8.8% (model (4)) to 9.8% (model (7)) lower than the heating expenditures in modernized tenant-occupied dwellings. Nontheless, homeowners belonging to the *treated household group 1* generally have by 4.3% (model (4)) to 4.9% (model (7)) higher expenditures and homeowners of the *treated household group 2* have even higher expenditures. These comparably high energy expenditure levels indicate the need of renovation or a lavish energy consumption behavior of treated homeowners.

The isolation of the effects (i.e. $\delta_{9,10}$) of modernizations made by owners during the two subsidy program periods shows an increase for both periods, by 12.7% (model (6)) to 13.7% (model (5)) for the first and by about 13% for the second program period. These positive impacts indicate that the modernizations do not decrease heating expenditures of homeowners of the *treated household group 1* during the subsidy periods. On the contrary, modernization measures made by owners during the subsidy period even lead to higher heating expenditures. These higher heating expenditures may be caused by dwelling modernizations that increased energy consumption such as dwelling extensions and proves that homeowners did not sufficiently invest in energy-efficiency or that they overconsume energy after the investment. These effects control for the generally lower heating expenditures of owners and for the treated household types.

Figure 7 sums up the results and presents the differences between the two treated household types in owner- and tenant-occupied dwellings. Figure 7 displays the distributions of real heating expenditures for households that did not modernize between 1996 and 2010, for owners and tenants separately. In addition, the distributions of expenditures of households that modernized are shown, before and after the renovation, again separately for owners and tenants. In summary, households comprised of owners exhibit significantly lower heating expenditures than tenant households and invest more in energy efficiency than landlords. By isolating the impact of the already lower heating expenditures of owners, it can be seen that the modernizations made during the subsidy period result in reduced heating expenditures for tenants but not for owners. More than half of the subsidies were paid to owners. Thus, it can be concluded that owners make significant windfall profits when they are willing to renovate and invest in energy efficiency, even without subsidies.

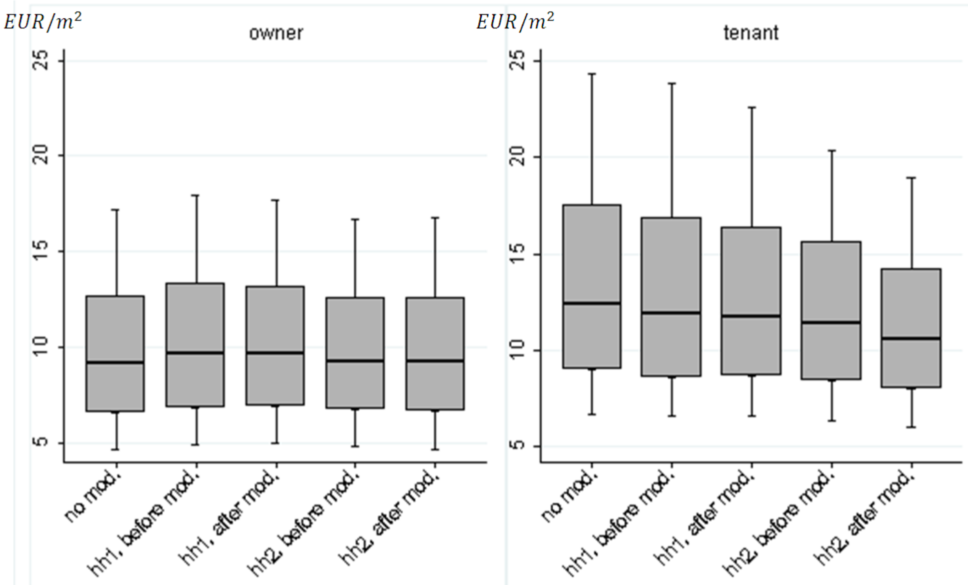

Figure 7: Treatment effect on real heating expenditures in Euros per m^2
The whiskers of the boxplots indicate the 10% to 90% range.
'no mod.' indicates households that did not modernize their dwelling between 1992–2010.
'hh1' ('hh2') are households that invested in 1996–2002 (2003–2010).
'before' and 'after' indicates the real heat. exp. before and after the modernization.

7. Conclusion

Households are heterogeneous concerning their socio-economic characteristics and the state of their dwellings. Hence, the reasons for and the degree of investment inefficiencies are diverse. The theoretical and empirical results show the importance of the heterogeneity of households, as well as the impact of their socio-economic characteristics on investments in energy efficiency and on energy consumption. The effectiveness of policy measures is determined by varying credit constraints and the different valuation of energy savings of households. The results of this paper thus support the results of Brounen et al. (2012) reiterating that socio-economic aspects need to be taken into account in order to develop an optimal policy design. Accounting for the heterogeneity of households is crucial in the design of targeted policies.

The landlord-tenant problem in the German heating market represents a restrictive investment barrier. Investments responsible for decreasing energy consumption mostly occur in owner-occupied dwellings as opposed to tenant-occupied ones. The presented paper provides evidence for this principal-agent problem and the lack of investments in tenant-occupied dwellings. Thus, the energy efficiency gap is broadened by the landlord-tenant problem.

The empirical results show only slight increases in the probability of dwelling modernizations in owner-occupied dwellings throughout the subsidy programs. Therefore, a quantity effect, i.e. when a subsidy leads to more dwelling modernizations, cannot be found for investments made by landlords in tenant-occupied dwellings. However, modernizations made during subsidy periods significantly decrease energy expenditures in tenant-occupied dwellings. Households who own their dwelling generally have significantly lower heating expenditures (by about 20%) than tenants and renovate more often than landlords. The modernizations made by owners during the subsidy program periods did not further decrease their heating expenditures. Homeowners invest in energy efficiency even without subsidies and could realize significant windfall profits through the subsidy payments. Furthermore, a higher income of owners indicates to a lower probability of credit barriers and a higher probability of windfall profits. Thus, the subsidies reflect an indirect redistribution of income to a group that is already economically better off.

The impact of energy prices on heating energy consumption is heterogeneous. Whereas tenants exhibit a high price elasticity, the price elasticity of owners is low. Therefore, the rebound effect in tenant-occupied dwellings may be larger than in owner-occupied ones, which can again be traced back to the landlord-tenant problem. Higher energy consumption of tenants due to insufficient renovations by landlords increase the price sensitivity of tenants and may further counteract the effectiveness of the subsidies.

The investment barrier in tenant-occupied dwellings first needs to be directly eliminated before policy measures can be implemented. Changes in tenancy law and the resolving of information asymmetries between tenants and owners concerning the energy consumption of dwellings may lower the investment barrier. The provision of information and the transparency of the heating energy requirements of dwellings may affect the choice of potential tenants and increase investments by landlords in energy efficiency.

Institutional adaptations (e.g. adaptations of the rental law) to increase incentives for landlords to independently invest may be more effective in achieving energy and greenhouse gas conservation objectives. However, such changes may have other welfare effects. Moreover, demographical changes such as increases in dwelling size and reduction of household members may counteract energy-savings in the future. An analysis of policies accounting for such effects is open for further research.

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Appendix A. Summary statistics

Appendix B. Theoretical framework

In recent economic literature, there are different economic reasons why government should intervene in the market and introduce policies on energy efficiency to reduce energy intensities:

- Internalizing externalities such as greenhouse gas emissions
- Reducing the consumption of fossil fuels
- Correcting market failures on the household level (such as credit barriers or inefficiently high personal discount rates caused by market failures for energy savings)

Reasons for following the second objective include supporting sustainability of finite energy resources and keeping energy prices low.[16] The last point is a further issue that may be another barrier for policymakers to overcome while addressing the first two objectives. Inefficiently high personal discount rates for energy savings mean that the evaluation of energy savings from investments by households is inefficient.

The internalization of externalities and the maximization of energy savings in the private housing sector are addressed by national policy by enhancing investments in energy efficiency. Two popular policy measures on energy efficiency are lump-sum subsidies and subsidies on interest rates of investments in energy efficiency. The policies are introduced in a basic theoretical model presented by Allcott and Greenstone (2012) and Allcott et al. (2011). The socially optimal levels of policy measures are derived accounting for the household investment condition in energy efficiency. It is assumed that an energy efficiency gap exists. Policies can increase welfare because the investments made by households into energy-consuming systems are not economically efficient, i.e. the private net present value of energy savings following the investment is lower than the social net present value.

The consumer (or household) i is willing to make an investment in an energy-efficient good if the following condition holds:

$$\frac{\gamma_i m_i p(e_0 - e_{1,i})}{1+r} - \epsilon \geq c_i \qquad \text{(B.1)}$$
$$\text{with } c_i = c$$

The household i may make an investment in energy efficiency at cost c_i to achieve energy savings $e_0 - e_1$, where e_0 and e_1 are the energy intensities before and after the investment with $e_0 > e_1$, and p are the private cost of energy. For e_1, the model differentiates between $e_{1,i}$ and $e_{1,s}$. The optimal social energy intensity $e_{1,s}$ is conditional on the socially optimal investment level c with $e_{1,i} \geq e_{1,s}$. The privately chosen energy intensity $e_{1,i}$ reflects either a potential rebound effect, in a case in which the energy efficiency level c has been invested or the result of underinvestment in energy efficiency c_i such that $c_i < c$. Thus, it is assumed that the energy intensity level realized by the investment $e_{1,i}$ may be larger than the social level and lower than the level before the investment ($e_{1,s} \leq e_{1,i} \leq e_0$). For simplification, each household i chooses only one level within this range.

Variable m_i with $0 < m_i$, indicates household specific preferences concerning the energy consumption (or usage of the energy-consuming good) and $m_i = 1$ in case of homogeneous preferences among all households. In the case of $m_i > 1$, household i's energy usage is higher, and in the case of $m_i < 1$, the energy usage is lower than average. The term γ_i reflects the implied discount rate of household i and $\gamma_i \neq 0$ indicates behavioral misperceptions of the implied discount rate.[17] The term $\gamma_i < 1$ indicates an undervaluation of energy savings. Reasons why γ_i may be low or even close to zero include market failures such as a lack of

[16] This paper focuses on the achievement of energy savings through policy interventions. An evaluation whether it is an economically appropriate approach to strive for energy savings or especially fossil fuel savings requires a much larger temporal and geographical scope and will not be addressed.

[17] Allcott and Greenstone (2012) consider γ instead of γ_i.

information or principal-agent problems. Principal-agent problems occur when the investment decision in energy-efficiency is made by other parties than those who are confronted with the energy expenditures (see Jaffe and Stavins (1994)). Another cause may be low energy price elasticities of demand. The variable r is the specific risk-adjusted discount rate. In total, the energy savings (or decrease of energy intensity) $e_0 - e_1$ is discounted by the factor $\frac{\gamma_i m_i}{1+r}$. The opportunity costs of an alternative investment are indicated by ϵ. The model differentiates between two periods: In the first period, the household makes the investment in an energy-consuming system (investment period) and in the second period, the system is applied and energy is consumed (consumption period).

The household's investment condition deviates from a social optimum as the household neglects the externality φ. In addition, the optimal investment level in energy efficiency may not be achieved if the household is confronted with a credit barrier.[18]: In the case of a credit barrier, the willingness to pay of consumer i is $c_i < c$ or it is a more restrictive credit barrier which does not allow a consumer i to get a credit c for the investment in energy efficiency at all. Thus, given a credit barrier, c_i is always assumed to be smaller than the efficient investment level c ($c_i < c$), which causes an underinvestment in energy efficiency as $e_{1,s}$ is conditional on c. There could be different reasons why a household is not willing or able to invest at all. The credit barrier could be caused by a lack of sufficient income, a lack of information or other reasons. A restrictive credit barrier is simplified within the presented theoretical approach by indicating that in this case $\gamma_i \to 0$ such that any policy measure would be ineffective to encourage the household to invest.

The socially optimal energy efficiency level $e_{1,s}$ is below the private energy efficiency level chosen by household i $e_{1,s} \leq e_{1,i}$. A social optimum internalizing the costs of the externality φ and reaching the socially optimal energy efficiency level[19] $e_{1,s}$ would be the following:

$$\frac{m_i(p+\varphi)(e_0 - e_{1,s})}{1+r} - \epsilon \geq c \tag{B.2}$$

The next sections introduce two different policies that are applied in Germany – lump-sum subsidies and subsidies on interest rates – to this framework. The optimal social tax and subsidy levels are derived. So far, this basic theoretical framework has mainly been presented by Allcott and Greenstone (2012). The introduction of policies in the next sections are further developed by the author.

Appendix B.1. The energy efficiency gap

An intervention of public policy is only required if an energy efficiency gap exists. The energy efficiency gap may be defined as the difference between the social and the private gain of the investment in energy efficiency:

$$g_e = m_i(p+\varphi)(e_0 - e_{1,s}) - c(1+r) - (\gamma_i m_i p(e_0 - e_{1,i}) - c_i(1+r)) \tag{B.3}$$

The energy efficiency gap g_e reflects the net social gain of the energy efficient investment. The energy efficiency gap g_e is the deviation of the value of the private investment $\gamma_i m_i p(e_0 - e_{1,i}) - c_i(1+r)$ from the value of the socially optimal investment in energy efficiency $m_i(p+\varphi)(e_0 - e_{1,s}) - c(1+r)$. The social gain is achieved through the internalization of the externality and the reduction of energy consumption. To get the net social gain, the value of the energy savings that would have been achieved without any policy intervention is deducted from the social value of energy savings.

[18]The inclusion of the credit barrier is an extension of the model of Allcott and Greenstone (2012) made by the author.
[19]Here, the socially optimal energy efficiency level means an economically efficient usage of energy.

Appendix B.2. Lump-sum subsidies for investments in energy efficiency

Subsidies for energy efficient investments could be introduced to overcome potential credit barriers $c_i < c$. The household is willing to invest if:

$$\frac{\gamma_i m_i p(e_0 - e_{1,i})}{1+r} - \epsilon \geq c_i \qquad \text{(B.4)}$$
$$\text{with } c_i \geq c - s$$

The private benefits of the energy savings must be higher than the expected household's willingness to pay incorporating the subsidy.
For the socially optimal subsidy s_s the following must hold:

$$\frac{\gamma_i m_i p(e_0 - e_{1,i})}{1+r} - c_i + s_s = \frac{m_i(p+\varphi)(e_0 - e_{1,s})}{1+r} - c$$
$$s_s = \frac{m_i(p+\varphi)(e_0 - e_{1,s}) - c(1+r) - (\gamma_i m_i p(e_0 - e_{1,i}) - c_i(1+r))}{1+r} \qquad \text{(B.5)}$$

The optimal subsidy level s_s must thus equal the discounted deviation of the private valuation of energy savings $(\gamma_i m_i p(e_0 - e_{1,i}) - c_i(1+r))$ from the optimal social value of energy savings $m_i(p+\varphi)(e_0-e_{1,s})-c(1+r)$.

The deviation in the numerator equals the energy efficiency gap g_e in the consumption period. Thus, we get:

$$s_s = \frac{g_e}{1+r} \qquad \text{(B.6)}$$

Thus, the optimal subsidy s_s equals the discounted energy efficiency gap g_e.

The consumer's undervaluation of energy savings γ_i, the usage of energy m_i as well as the energy savings independently realized by the household $(e_0 - e_{1,i})$ reduce the effectiveness of the subsidy and thus both reduce the optimal subsidy level. The lower the willingness to pay of the household c_i or the higher the credit barrier $c - c_i$ the higher the subsidy needs to be.
A subsidy is able to correct for credit barriers. However, it does not affect the household behavior after the investment and cannot mitigate a rebound effect. In addition, for households that would invest anyways, the subsidy is a windfall.

Appendix B.3. Subsidies on interest rates of investments in energy efficiency

Subsidies on interest rates aim at decreasing the financing costs of households and address potential credit barriers $c_i < c$.
The household is willing to invest if:

$$\frac{\gamma_i m_i p(e_0 - e_{1,i})}{1+r-s} - \epsilon \geq c_i \qquad \text{(B.7)}$$
$$\text{with } c_i \geq c$$

where s is the subsidy, i.e. the percentage of the investment and financing cost $(c(1+r))$ that is subsidized. The private benefits of the energy savings discounted with the reduced interest rate $(r - s)$ must be higher than the expected household's willingness to pay.
For the socially optimal subsidy s_s, the following must hold for each household i:

$$\frac{\gamma_i m_i p(e_0 - e_{1,i})}{1+r-s_s} - c_i = \frac{m_i(p+\varphi)(e_0 - e_{1,s})}{1+r} - c$$
$$s_s = \frac{m_i(p+\varphi)(e_0 - e_{1,s}) - c(1+r) - (\gamma_i m_i p(e_0 - e_{1,i}) - c_i(1+r))}{\frac{m_i(p+\varphi)(e_0-e_{1,s})}{1+r} - (c - c_i)} \qquad \text{(B.8)}$$

Replacing the numerator by the energy efficiency gap g_e, Equation B.8 can be rewritten as follows:

$$\frac{g_e}{\frac{m_i(p+\varphi)(e_0-e_{1,s})}{1+r} - (c - c_i)} \tag{B.9}$$

The optimal subsidy level must equal the level of the energy efficiency gap in the consumption period (numerator) relative to the net social gain of the investment in energy efficiency in the investment period (denominator). Here, the net social gain of the investment in energy efficiency in the investment period is the value of the social energy savings level internalizing the externality $m_i(p+\varphi)(e_0 - e_{1,s})$ minus the credit barrier $c - c_i$ (or the additional investment capital needed for the socially optimal investment level).

As for the lump-sum subsidy, the consumer's undervaluation of energy savings γ_i, the usage of energy m_i as well as the energy savings independently realized by the household $(e_0 - e_{1,i})$ decrease the effectiveness of the subsidy and thus both reduce the optimal subsidy level. A high willingness to pay of the household c_i also reduces the optimal subsidy level. On the other hand, an increasing credit barrier results in a higher optimal subsidy level s_s.

To summarize, subsidies can be quite effective in reducing credit barriers or inefficiencies of the investment caused by high discount rates (γ_i) for energy savings, but not in reducing overconsumption of energy after the investment (Train, 1985; Allcott and Greenstone, 2012). However, for households that would also invest in energy efficiency without policy intervention, a subsidy is a windfall.

Appendix B.4. Investment barriers in tenant-occupied dwellings

In the German housing market, landlords are confronted with barriers to internalize the positive externalities of investments made in dwellings because of existing impediments concerning rent prices. On one hand, rent controls restrict the landlords from including investment costs in the current rent price. On the other hand, the independence of heating expenditures from rents and the lack of information on gross warm rent tenants are confronted with, additionally impedes the inclusion of investment costs in rent prices.

Moreover, tenants are not willing to make investments in energy efficiency as they are relationship-specific. A major part of the investment's value is lost when the tenant moves out. This risk of expropriation significantly reduces the tenant's incentive to make the investment himself (see Gebhardt (2012)). In the context of the analysis of investments in energy efficiency, this specific principal-agent is often referred to as the landlord-tenant problem (Jaffe and Stavins, 1994).

The landlord assumes a very high discount rate of energy savings ($1 > \gamma_i > 0$). To illustrate how this may impact the optimal subsidy level, we consider the extreme case in which the landlord may not be able to adapt the rent and benefit from energy savings: $\gamma_i \to 0$. This leads to the maximal energy efficiency gap g_e in tenant-occupied dwellings:

$$\begin{aligned}\lim_{\gamma_i \to 0} g_e &= \lim_{\gamma_i \to 0} \left(m_i(p+\varphi)(e_0 - e_{1,s}) - c(1+r) - (\gamma_i m_i p(e_0 - e_{1,i}) - c_i(1+r))\right) \\ &= m_i(p+\varphi)(e_0 - e_{1,s}) - (c - c_i)(1+r)\end{aligned}$$

In this case, the energy efficiency gap equals the social value of the sum of the internalization of the externality and the social optimal energy intensity $m_i(p+\varphi)(e_0 - e_{1,s})$ minus the additional amount that is needed to be able to make the energy-efficient investment $(c - c_i)(1+r)$.

The landlord's investment condition $\frac{\gamma_i m_i p(e_0 - e_{1,i})}{1+r} - \epsilon \geq c$ can hardly be fulfilled as $\lim_{\gamma_i \to 0}$ because the tenant would profit mainly from an investment in energy efficiency and the landlord can scarcely internalize this positive externality, which results in an underinvestment problem in energy efficiency and higher energy consumption levels of tenants.

The socially optimal subsidy level to promote the landlord's investment is then:

$$\lim_{\gamma_i \to 0} s_s = \lim_{\gamma_i \to 0} \left(\frac{g_e}{\frac{m_i(p+\varphi)(e_0-e_{1,s})}{1+r} - (c - c_i)} \right) \tag{B.10}$$

$$= \left(\frac{m_i(p+\varphi)(e_0 - e_{1,s}) - (c - c_i)(1+r)}{\frac{m_i(p+\varphi)(e_0-e_{1,s})}{1+r} - (c - c_i)} \right) = 1 + r \tag{B.11}$$

As s_s indicates a percentage level, the absolute level of the optimal subsidy would be $c(1+r)$. Hence, in the extreme case ($\lim_{\gamma_i \to 0}$), the subsidy would need to compensate for the total investment and financing costs.

Appendix B.5. Subsidies, the heterogeneity of households and information assymetries of policy makers

To be able to set the optimal level of a subsidy (either a lump-sum or a subsidy on interest rates), the policy maker has to know the investment household i needs to make to achieve the optimal level of energy savings and abatement of the externality. Thus, he needs to know all the parameters of Equation B.2. In this simplified illustrative model, there is just one socially optimal investment level c and energy intensity level $e_{1,s}$. However, in reality the optimal investment and energy intensities would vary among households. Risk-adjusted discount rates may further depend on houseold i.

Moreover, even the heterogeneity of households captured by the model does not allow policy makers to introduce first-best subsidies. The policy maker would need to have private information on all parameters of Equation B.2 because first-best policies would need to be household-specific without causing additional administration costs. The less heterogeneous the population is and the closer the policy measures are set to the optimal level for a median household, the more efficient is the market outcome. The policy maker is confronted with information assymetry concerning the individual preferences of energy usage m_i, the undervaluation of energy savings γ_i and a potential rebound effect $e_{1,i}$. To determine a second-best subsidy level s_s the policy maker could include the average energy usage $\overline{m} = \sum_{\forall i} m_i$ instead of m_i based on empirical data. Nevertheless, information on a potential rebound effect $e_{1,i}$ is not available to the policy maker. Thus, he will build expectations $E[e_{1,i}]$. If the policy maker underestimates the rebound effect $E[e_{1,i}] < e_{1,i}$, the expected energy efficiency gap will be smaller than the real efficiency gap $E[ge] < ge$. Then the subsidy s chosen by the policy maker is below the optimal subsidy $s < s_s$ and the energy efficiency objectives are not achieved. In case of an overestimation $E[ge] > ge$, the subsidy is set inefficiently high $s > s_s$ which may cause welfare losses and may provide potential windfall profits to households.

Nonetheless, despite the unlikelihood that a policy maker may set the optimal subsidy s_s, the actual subsidy set may still be able to reduce energy consumption and reduce the externality. It may be that households were not able or willing to invest at all and even a suboptimal subsidy may reduce the credit barrier. Thus, even though the level $e_{1,s}$ cannot be achieved, reducing the energy to the level $e_{1,i}$ is already an improvement compared to e_0 as long as the investment and subsidy costs are lower for society than the costs of the externality. A subsidy may therefore increase the number of investments in energy efficiency made by households (Hypothesis 1).

It may also be that a household, who is willing to invest in energy efficiency may be encouraged by the subsidy to choose a higher investment level than the initial one c_i. Such an investment level may be between c_i and c and the resulting energy intensity would be between $e_{1,i}$ and $e_{1,s}$. A subsidy may therefore reduce the energy consumption of a household (Hypothesis 2).

Moreover, if the policy maker has asymmetric information about the landlord-tenant problem and the level of γ_i, he will have difficulties in estimating the energy efficiency gap g_e and in setting an optimal subsidy, which may impact the effectiveness of a subsidy (Hypothesis 3). In addition, if γ_i differs significantly between owners and tenants, the policy maker may need to introduce separate subsidies for investments in owner- and tenant-occupied dwellings.

Appendix C. Summary statistics

Table C.5: Summary statistics: Estimation A

Variable	Mean	Std. Dev.	Min.	Max.	N
dwelling modernizations	0.059	0.235	0	1	125686
owner-occupied	0.474	0.499	0	1	125686
log. of adj. income	7.685	0.605	0	11.531	125686
household type	2.876	1.704	1	8	125686
construction period	3.404	1.527	1	7	125686
number of relocations	0.594	1.119	0	12	125686
number of rooms (> 6 m^2)	3.942	1.734	1	22	125686
need of renovation	1.319	0.521	1	4	125686
subsidy ratio	0.104	0.078	0	0.29	125686

Table C.6: Summary statistics: Estimation B, owner

Variable	Mean	Std. Dev.	Min.	Max.	N
logarithm of heating expenditure per m^2	2.119	0.603	-5.075	5.051	56022
heating expenditure	1168.296	697.893	1	9999	56022
dwelling size in m^2	125.388	44.664	10	650	56022
owner-occupied	1	0	1	1	56022
HDD	262663.021	39374.617	63908	356910	56022
log. of gas price	4.518	0.251	4.143	4.881	56022
log. of adj. income	7.913	0.567	3.526	11.531	56022
household type	3.194	1.722	1	8	56022
construction period	3.537	1.603	1	7	56022
number of relocations	0.37	0.865	0	9	56022
number of rooms (> 6 m^2)	4.938	1.703	1	20	56022
need of renovation	1.202	0.418	1	4	56022

Table C.7: Summary statistics: Estimation B, tenant

Variable	Mean	Std. Dev.	Min.	Max.	N
logarithm of heating expenditure per m^2	2.366	0.496	-0.693	4.692	46513
heating expenditure	901.33	526.877	36	11160	46513
dwelling size in m^2	78.079	29.204	9	938	46513
owner-occupied	0	0	0	0	46513
HDD	263994.771	36608.335	63908	356910	46513
log. of gas price	4.449	0.258	4.143	4.881	46513
log. of adj. income	7.53	0.54	3.584	10.645	46513
household type	2.722	1.659	1	8	46513
construction period	3.192	1.39	1	7	46513
number of relocations	0.743	1.252	0	12	46513
number of rooms (> 6 m^2)	3.133	1.195	1	22	46513
need of renovation	1.445	0.584	1	4	46513

Table C.8: Summary statistics: Estimation B, all

Variable	Mean	Std. Dev.	Min.	Max.	N
logarithm of heating expenditure per m^2	2.231	0.570	-5.075	5.051	102535
heating expenditure	1047.192	640.079	1	11160	102535
dwelling size in m^2	103.927	45.072	9	938	102535
owner-occupied	0.546	0.498	0	1	102535
HDD	263267.143	38150.194	63908	356910	102535
log. of gas price	4.487	0.256	4.143	4.881	102535
log. of adj. income	7.739	0.587	3.526	11.531	102535
household type	2.98	1.71	1	8	102535
construction period	3.38	1.52	1	7	102535
number of relocations	0.539	1.075	0	12	102535
number of rooms (> 6 m^2)	4.119	1.744	1	22	102535
need of renovation	1.312	0.515	1	4	102535
modernized	0.347	0.476	0	1	102535
treated household group 1	0.186	0.389	0	1	102535
treated household group 2	0.222	0.416	0	1	102535

Appendix D. Subsidy programs

The high greenhouse gas reduction objectives self-imposed by the German government require effective measures to enhance energy efficiency. Various measures are listed in the National Energy Efficiency Action Plan (NEEAP) of the Federal Republic of Germany (Federal Ministry of Economic Affairs and Technology, 2007) to promote investments in energy efficiency in residential dwellings. The Credit Institute for Reconstructions (Kreditanstalt für Wiederaufbau (KfW)) CO_2 building redevelopment program and the KfWs living space modernization program as part of the EEAP are major subsidy programs that promote investments in energy efficiency in the residential building stock. The KfW spent more than 38 billion Euros on these two programs in Western Germany between 1996 and 2010, which was mainly financed through government funds. 255 million Euros of the total 38 billion Euros spent were lump-sum payments and the major part of the subsidies have been provided through subsidized credits (subsidies on interest rates). Both programs subsidize investments in energy efficiency but differ in terms of their promotional framework. The CO_2 building redevelopment program had been modified in 2001 and the KfWs living space modernization program had been modified in 2005. The four project variations are summarized in Table D.9.

Table D.9: Subsidy programs

		Objective	**Options**	**Instruments**
CO_2 reduction program (CO_2-Minderungsprogramm)	1996–2005:	Reduction in CO_2 emissions	CO_2-saving measures to buildings	Subsidies on interest rates, repayment bonus
Energy efficient reconstruction (Energieeffizient Sanieren/ CO_2-Gebudesanierungsprogramm)	Since 2001:	Promotion of energy-saving and CO_2-reducing measures to existing buildings	Insulation, install ventilation, Exchange: windows, heating; Conversion of buildings to fulfill KfW energy efficiency standard	Investment grants, repayment bonus, government loans
Residential property modernization program 2003 (Wohnraummodernisierungs-program 2003)	2003–2004:	Promotion of modernization and repair of housing	Modernization and repair of housing, Dismantling of vacant buildings, Improving the housing environment	Subsidies on interest rates, Low-interest loans
Modernization of residential property (Wohnraum Modernisieren)	2005–2011:	Promotion of energy-efficient renovations	Insulation, install ventilation, Exchange: windows, heating	Investment grants, government loans, repayment bonus